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By

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Submitted in partial fulfillment

for the requirements

for the degree of

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PREFACE

In the course of several years experience as a naval communications officer and as an active radio amateur the writer has noticed a wide variation in efficiency of transmitter installations using antennas much shorter than a quarter-wavelength, a variation between comparable installations of as much as several hundred to one. The question arose as to the cause of this wide variation in installations which were using transmitters of approximately the same power output and short antennas of approximately the same fraction of a wavelength. The differences apparent were differences in short antenna configuration method of loading and of transmission line termination. Was the inefficiency of some systems to be blamed upon the loading system in use, the operator, or the type of short antenna used?

It was to answer this question that initial work was begun during the first year of a three year post-graduate course in electronics at the U.S. Naval Post-graduate School.

The field under study is by no means a new one. Antenna engineers have been faced with the problem of

[illegible]

[illegible]

[illegible]

[illegible]

too little antenna space since radio communications were first begun. One must humbly realize that there is small probability of accomplishing a tremendous innovation in a field so thoroughly explored by so many competent engineers during the course of the past fifty years. Yet, as the art progresses it will be more repeatedly necessary for young engineers to re-examine such older fields of endeavor in the late of the latest techniques so that the basic concepts involved, and the work of their predecessors will not be forgotten.

The study of an older field has convinced the writer that there is serious danger of this happening in the electronics field, a field advancing so rapidly that complete coverage along the line of advance is impossible, and that one of the differences between a great engineer and a mediocre one is the formers ability to remember the text book source of and apply the very basic concepts, to humbly recognize that he has been preceeded by many better engineers whose published investigations are very well worth investigating.

SUMMARY

The short antenna problem may be stated relatively simply. If we ignore control of the magnitude and direction of radiation of an antenna, then a very small antenna will theoretically radiate as well as a larger or resonant one, provided that the generating source be capable of supplying a driving voltage and current in the proper ratio or source impedance. This impedance is, for antennas increasingly less than a quarter-wavelength long, increasingly capacitive. Thus, to drive a current of any magnitude through the small radiation resistance of the equivalent series circuit requires developing a high potential across the small capacitor of that equivalent circuit.

Unfortunately, radio transmitters prefer to be operated into loads whose power factors are much closer to unity. Of necessity, therefore, we must supply, either in the antenna itself, or between the transmitter and antenna a large inductive reactance, so that the net impedance, "looking towards" the antenna from the transmitter will be largely resistive.

The efficiency of such a system is merely the percentage of the resultant resistance component representing the radiation resistance of the antenna referred to that point.

Unfortunately then, the shorter the antenna, the greater the inductive reactance required, and hence the greater the inductance and consequent losses in that inductance. In addition, there are losses representing the fact that the return path for the circuit is through water or ground of finite conductivity, and losses due to imperfect junctions and transmission lines that can no longer be considered lossless at increasingly greater lengths, or standing wave ratios.

There are several methods in current use for inserting the required inductive reactance in the system, and for minimizing the magnitude of the inductance required, and minimizing the losses of that inductance. By establishing a "figure of merit" for several systems and showing that they have approximately the same value for each system, the writer concludes that no particular method of inserting the required inductance, or "loading" has an obvious merit over any other equally well-engineered system. One of the systems thus examined is

[illegible]

[illegible]

[illegible]

[illegible]

the system of "distributed loaded", or "helical" antenna, for which simplified design equations are developed, considerations not previously available in the literature.

To show the possibility of accurately calculating the efficiency of any proposed system, three methods of calculation are demonstrated for several systems, and measurements made to confirm in the field the validity of the efficiency calculations.

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TABLE OF SYMBOLS AND ABBREVIATIONS

A	Area of a loop $(ft)^2$ or degree-ampere product
a	Whip Diameter (inches)
a_c	Coil Diameter (inches), loop diameter (ft.)
Ca	Numerical value of the capacitance of the driving point reactance of an unloaded whip, or section of a loaded whip above the inductor
Cbi	Base insulator capacitance
C_c	Capacitance to ground of a close-wound loading coil, considering it a solid cylinder and applying equation (9)
Co	Distributed capacitance of a coil
Ct	Antenna top-loading capacitance
C'	Capacitance per foot (uuf/ft)
D	Number of degrees in the physical antenna length
d	Wire or top-loading element diameter (inches)
D_c	Number of degrees of transmission line length in a helix
f	Frequency (mcs.)
h	Antenna height (feet)
heff	Effective height (feet)
Ic	The r.m.s. current flowing out of a loaded antenna due to capacitive loading.
Io	The r.m.s. current into the base of an antenna
Il	The r.m.s. current flowing out of the top of a loading coil

K_Q	Ratio of effective to apparent coil Q
L	True inductance of a coil
La	Apparent inductance of a coil
L'	Inductance per foot (uh/ft)
lc	Coil length (inches)
l_w	Length of wire on a helix
m	The ratio of operating frequency to self resonant frequency of a coil
N	Turns per inch
n	Number of turns
P_r	Antenna radiated power (watts)
Q	Quality factor or figure of merit of a coil
Qa	Apparent Q of a coil with distributed capacitance
Qeff	The effective Q of a coil referred to a current anti-node
R	True series resistance (a.c.) of a coil
Ra	Apparent series resistance of a coil with distributed capacitance
Rb	Resistive component of base driving point impedance
Rc	Loss resistance of a whip antenna installation due to imperfect junctions
Rl	The effective loss resistance of a loading inductor referred to a current anti-node
Rr	Radiation component of the driving point impedance
Rd_c	True series D.C. resistance of a coil

Rbi	Base insulator resistance
Rtl	Transmission line resistance
Rg	Ground loss resistance
Vw/c	Ratio of wire apparent velocity to free space velocity
Xa	Reactive component of the driving point impedance of a short antenna
Xtl	Transmission line reactance
Zb	Base driving point impedance of short antenna
Zin	Transmitter end input impedance
Zo	Characteristic impedance of a transmission line
λ	Wavelength (feet)
wo	Self resonant frequency of a coil as measured by a grid - dip meter
w	Angular frequency (radians per second)
B	Phase shift per unit length (radians/ft)

CHAPTER I - THEORETICAL CONSIDERATIONS

1. Driving Point Impedance and Elementary Circuit Diagram

A circuit element which limits the amount of current flowing through itself to a given fraction, and at a given phase angle with respect to a driving voltage, is called an impedance. Resistors are distinguished by the fact that they consume power but have a zero phase angle, whereas neither inductors nor capacitors consume power, but the former causes a lagging current to flow, and the latter, a leading current to flow. Further, the magnitude of the fraction involved (or reactance) increases with frequency in the case of the capacitor, and decreases in the case of the inductor.

We summarize these characteristics by saying:

$$Z = R + j(X_L - X_c) \tag{1}$$

$$X_L = 1/JwL \tag{2}$$

$$X_c = 1/JwC \tag{3}$$

Further, should we "look into" any series or parallel arrangements with an <u>impedance</u> measuring device, we would measure and obtain directly the series components of <u>net</u> resistance and reactance. Should we make this

measurement with an admittance meter (the reciprocal of impedance) we would obtain the value of the net conductance and susceptance connected in parallel. Either set of numbers can, by proper algebraic manipulation, be converted to the other and we can properly represent the circuit in a simplified, but thoroughly valid way, by sketching and evaluating two circuit elements, the net series or parallel resistance or conductance, and net reactance, or susceptance.

Such a representation has many advantages. Its greatest advantage is its complete simplicity and the clarity with which it presents the net circuit parameters.

Now an antenna presents such an impedance to a driving voltage, because it consumes power (through circuit losses, and radiation) and therefore has a resistive component. Due to the fact that its length is not negligibly small compared to a wavelength, it introduces a phase shift in the current flowing in it. Further, this phase shift and resistive component are a function of the point along its length at which it is driven. Its impedance is therefore a function of

its length compared to a wavelength, and the point at which it is driven. Should this point be at a current anti-node there will be no reactive component, but only a resistive component, and this value of resistance has a particular name: "radiation resistance". However, in accordance with Chaney[1], we need not make this distinction, if we discuss only the "resistive and reactive components of driving point impedance".

Antennas whose length are so short that they have not reached their first resonance (at a quarter wavelength) present a resistive component less than some 36 ohms, and a reactive component which is capacitive in nature, and representing a value of capacitance which increases with length until, at a quarter wavelength, it reached infinity.

Unfortunately, in the case of a very short antenna much shorter than a wavelength, the reactive value is many times greater than the resistive value. Basically speaking, this is no problem, since we can deliver maximum power to any such impedance by merely supplying it from a generator whose internal impedance, as seen at the driving point, has a reactive value of equal and

opposite sign to that of the antenna driven. Of course, should the generator have a resistive component of internal impedance, all available power would not appear in the antenna as radiated power. Should the generator have a desired value of resistance into which it works best, e.g., the final Class C stage of a transmitter, then the antenna system will consume all the rated power output of the transmitter when it "sees" that value of impedance. THIS WILL OCCUR WHEN THE TRANSMITTER PLATE CURRENT READS MANUFACTURERS RATED VALUE WITH THE FINAL TANK CIRCUIT RESONATED, THAT IS, WITH THE FINAL PLATE CURRENT "DIPPED".

This is an extremely important point to accept, for it means, using tank circuits of high Q, and low loss transmission lines, that full power is being radiated, less ONLY THE LOSSES IN THE INTERVENING "MATCHING" SECTIONS.

We are now limited to only one method, basically, of operation: to insert lumped or distributed reactance in the matching system such that the transmitter final stage sees an almost pure resistance of value equal to the value recommended by the manufacturer for that value

of tube operating voltages and currents. The reactance thus coupled must be no greater than can be offset by a slight readjustment of the final plate tuning condenser.

Since the intervening matching and transmission circuits are not, in reality, lossless, we must minimize those losses. The system losses will be further discussed in sections 4 - 6 of this chapter.

We have so far discussed the equivalent circuit in very broad terms, as though that circuit contained only two components, the series resistive component and reactive component as measured by an impedance measuring instrument. In order to more accurately evaluate the factors affecting radiation efficiency it becomes necessary to separate the components of the circuit more fully. Such a separation is shown in the more complete equivalent circuit of Figure I.

2. Effective Height - The Radiation Resistance of a Short Antenna as Affected By Current Distribution

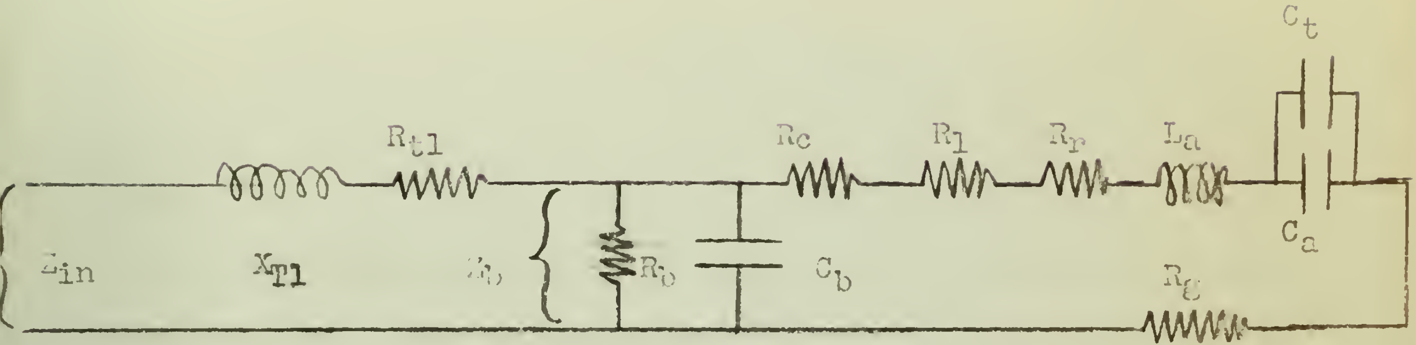
Terman[2] introduces the concept of antenna effective height in two ways, both of which being in reality the same,[3] but one applied to the antenna as a receiving, and one as a transmitting antenna.

a) As a receiving antenna:[16] Upon a receiving antenna we impress a field of intensity E uv./m, and measure the open-circuit voltage (V) developed at the antenna driving point terminals. The effective height is then merely the value, V/E [3,4]. (4)

b) As a transmitting antenna:[3] Measure the current at a current anti-node of the antenna under discussion, then substitute for it an antenna over which the current distribution is constant and of that value, and adjust its length until the same field is being radiated. The length of the second antenna is the effective length of the first.

The effective length of an antenna is never more than the physical length. With maximum loading they are equal. The variation in radiation resistance and therefore antenna efficiency with changing current distribution can be shown percentage-wise by using La Port's[5] concept of degree-amperes. After plotting current distribution of any random configuration versus length, we convert the length axis to degrees by multiplying by the factor $360/\lambda$ and graphically integrate to get the ampere-degree area (assuming maximum current of unity).

Equivalent Circuit Diagram of a Loaded Short Antenna



Sym	Component	Remarks
Z_{in}	Transmitter-end input impedance	Sending-end impedance
X_{tl}	Transmission-line reactance	Smith-chart solution
R_{tl}	Transmission-line loss resistance	Federal Handbook
Z_{bi}	Base impedance	As measured by GR 916(A) Bridge
R_{Bi}	Base insulator res.	Kandoian estimates power factor >< 1/1000
C_b	Base insulator cap.	Kandoian estimates 10 uuf. for 35' whip base
R_c	Connection loss res.	
R_l	Inductor loss res.	$2\pi fL/Q_{eff}$
R_r	Radiation res.	See Fig. II
L_a	Apparent inductance	As modified by C_o
C_a C_t	Antenna and top-load capacitance	Eqn (9) and Fig. III
R_g	Ground loss res.	$f(Z_o, f, I, \sigma) \sim 2$

Figure I

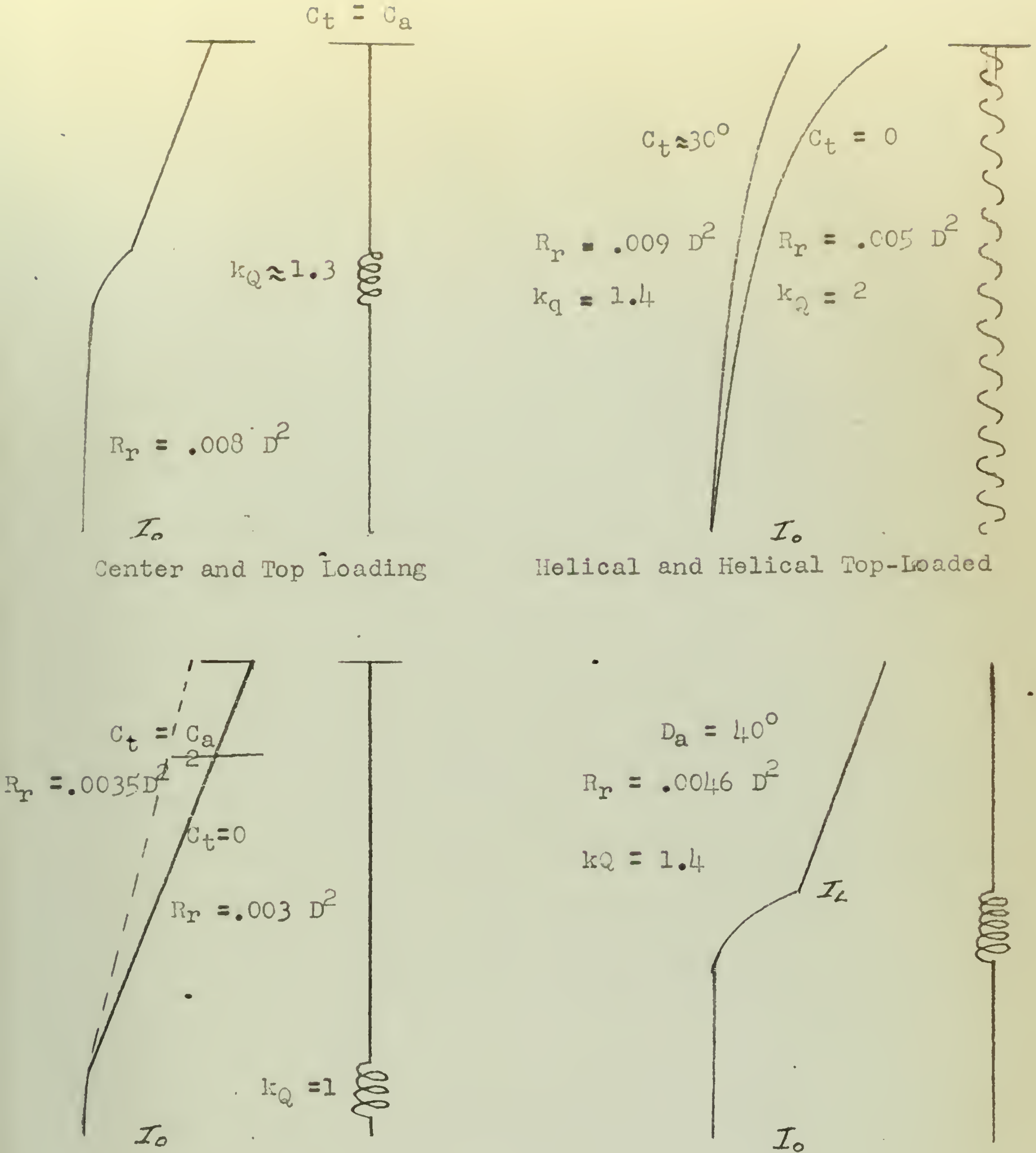
We can then apply the La Port equation;

$$Rr = .01215\ A^2 \qquad (5)$$

An example of how this re-distribution of current can improve the radiation resistance is given in Figure II, where D is the number of degrees physical length of the antenna. It is of interest to confirm these equations by using them to calculate typical radiation resistances as tabulated by Wrigley[6] from far field integrations. The results differ only by the factor 34/36, the approximate radiation resistances of thick and thin quarter-wave antennas, respectively.

3. The Reactive Component of Driving Point Impedance - Antenna and Top-Load Capacitance

Since we have agreed to discuss antennas operating at such a frequency that they are too short to have reached the quarter wavelength resistive operating point, such antennas will exhibit a reactive component of driving point impedance that will be capacitive. Further the value of this reactive component will decrease with frequency until, at the quarter-wavelength point, it will disappear entirely. Let us examine the nature of this variation with frequency. King [7] and LaPort [5] write the



$k_Q = Q_{eff}/Q_a$

$R_r = 0.01215\ G^2$
where G is the degree-ampere area under the current curve with I_o taken as unity

VARIOUS RADIATION RESISTANCE EQUATIONS FOR TYPICAL CURRENT DISTRIBUTIONS SHOWING EFFECTIVE COIL Q's.

FIGURE II

first term of the reactive component as:

$$X_a = -j60 \quad (\ln \overset{24}{\cancel{2}}h/a) \quad \cot 2\pi\, h/\lambda \qquad (6)$$

which would be infinite for an antenna approaching a length very, very small in terms of a wavelength, and go to zero for a quarter-wavelength antenna. It might become convenient for purposes of later design calculations to write this equation in other terms. We notice, for example that the reactance variation with frequency (assuming Cot X $\cong$ 1/x) is of the same nature as that of a capacitor. We might be able to express this variation as that of an equivalent capacitance. And this indeed we can do, if we accept a small error. The value of capacitance might be approximated by evaluating the above reactance at some intermediate frequency for a given antenna in terms of the capacitor which would have the same reactance at that frequency, that is:

$$C = \frac{1}{2\pi f X_c} \qquad (7)$$

This approximation is perhaps too much in error for our purposes, and instead we can derive by "logarithmic potential methods" of La Port[5] a more exact equation. The logarithmic potential method merely applies the equa-

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tions of electrostatics to a situation of moving charges. Such an equation would result as follows;[2]

$$C = \frac{7.36\, h}{\log_{10} \frac{24h}{a} - K} \quad \text{uuf.} \qquad (8)$$

where $K = \log_{10} e$ for antennas close to the ground, and decreases to .133 as the antenna is raised.

By combining (7) and (6) and assuming $\cot 2\pi h/\lambda$ is approximately equal to $\lambda/2\pi h$, we can arrive at (9). However, even this equation is perhaps too inexact, and we can include a factor which would correct for the fact that the curvature of a cotangent curve and an inverse curve are not exactly the same. Such an equation appears in the ARRL Amateur Handbook[24] (page 454) as the result of research and an article by Oberlies [9].

$$C = \frac{17h}{\left(\ln \frac{24h}{a} - 1\right)\left[1 - \left(\frac{fh}{246}\right)^2\right]} \qquad (9)$$

The frequency correction term, if omitted for antennas of length less than 20 degrees would cause an error of less than five percent, and we shall, therefore use equation (8), correcting to base e, giving (9) with the frequency correction term omitted.

One other factor is of significance, the relative magnitude of this capacitance for antennas which are center and base loaded. As the Amateur's Handbook[8](p.455) points out, the significant length in the determination of antenna capacitance for a loaded antenna is the length ABOVE any lumped loading used. Further, the value of this capacitance will be proportional to the length used, provided the ratio h/a is held constant.

There is at least one advantage to expressing the reactive component of driving point impedance as an equivalent antenna "capacitance to ground". Should we desire to raise our antenna efficiency, "equivalent height", or "terminating capacity" by adding some "top loading" or "capacity loading", we merely add the capacity added to the antenna capacity already present to calculate the new loading inductance required. This capacity is, from Dome[10];[11]

$$C = k_c\, d \qquad \text{uuf} \qquad (10)$$

where k_c = 1.425 for a sphere

= .9 for a disc

= 2.04 for a cylinder

and d is a diameter and the length of the cylinder, in inches.

One other point is of significance: the similarity between equation (6) and the input impedance to an open circuited transmission line as written by LaPort, for example [5]:

$$Z_{in} = -j\, Z_0 \cot Bh \qquad (11)$$

One can therefore evaluate the equivalent added line length due to an open circuited transmission line terminated in a capacitor. And it must be noted that a given capacitor will cause a greater equivalent line length addition when terminating a high impedance line than a low impedance one.

Figure III is a plot of this additional line length in terms of the ratio of Xc/Zo.[18]. We shall use this concept when discussing loaded antennas as transmission lines.

4. Factors Affecting the Efficiency of Short Antenna Systems

The efficiency of any antenna system is basically the ratio of the power radiated to the power input to the antenna system. One immediately asks whether the efficiency will have any effect on the efficiency of communications where an inefficient system is used. The

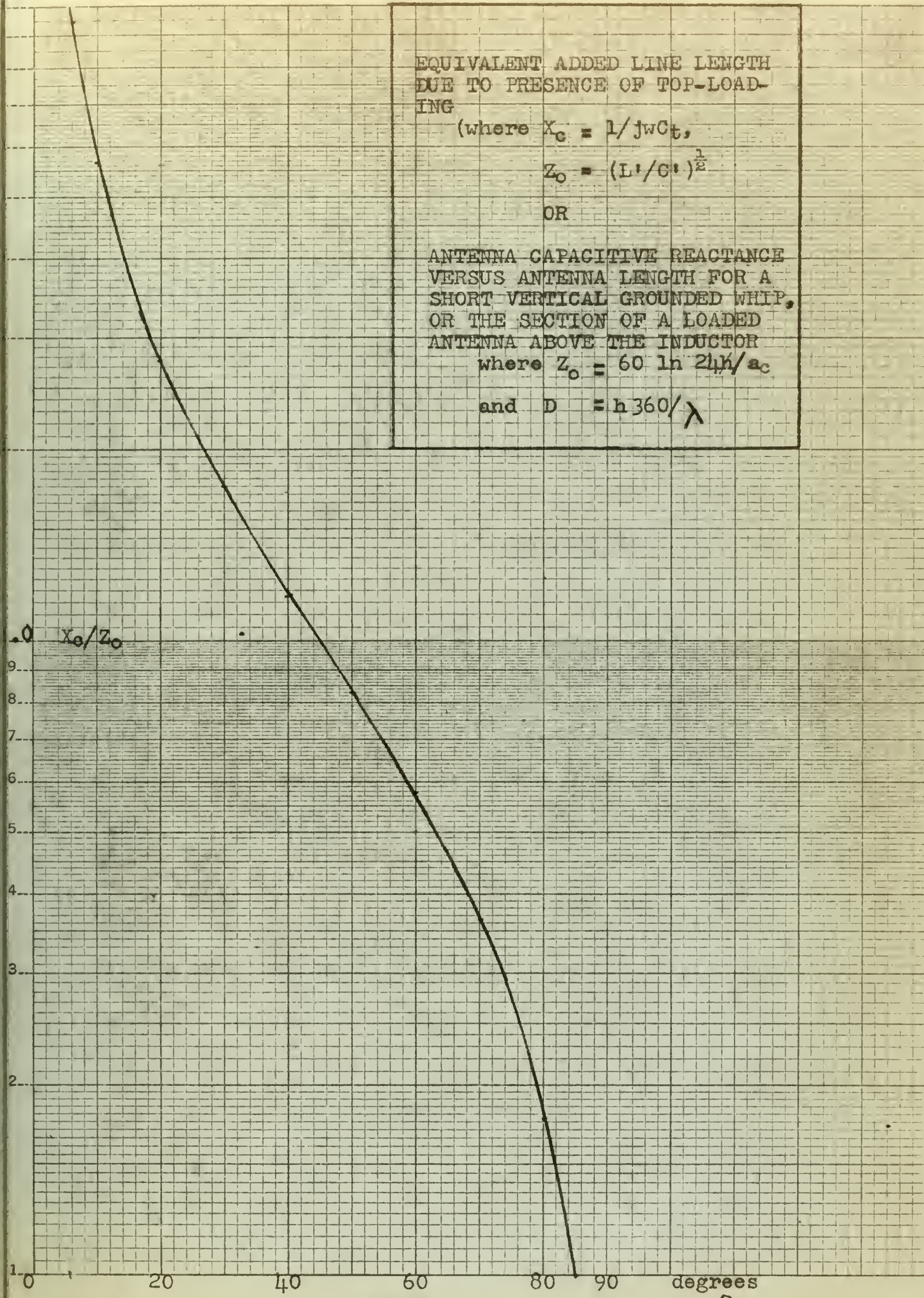
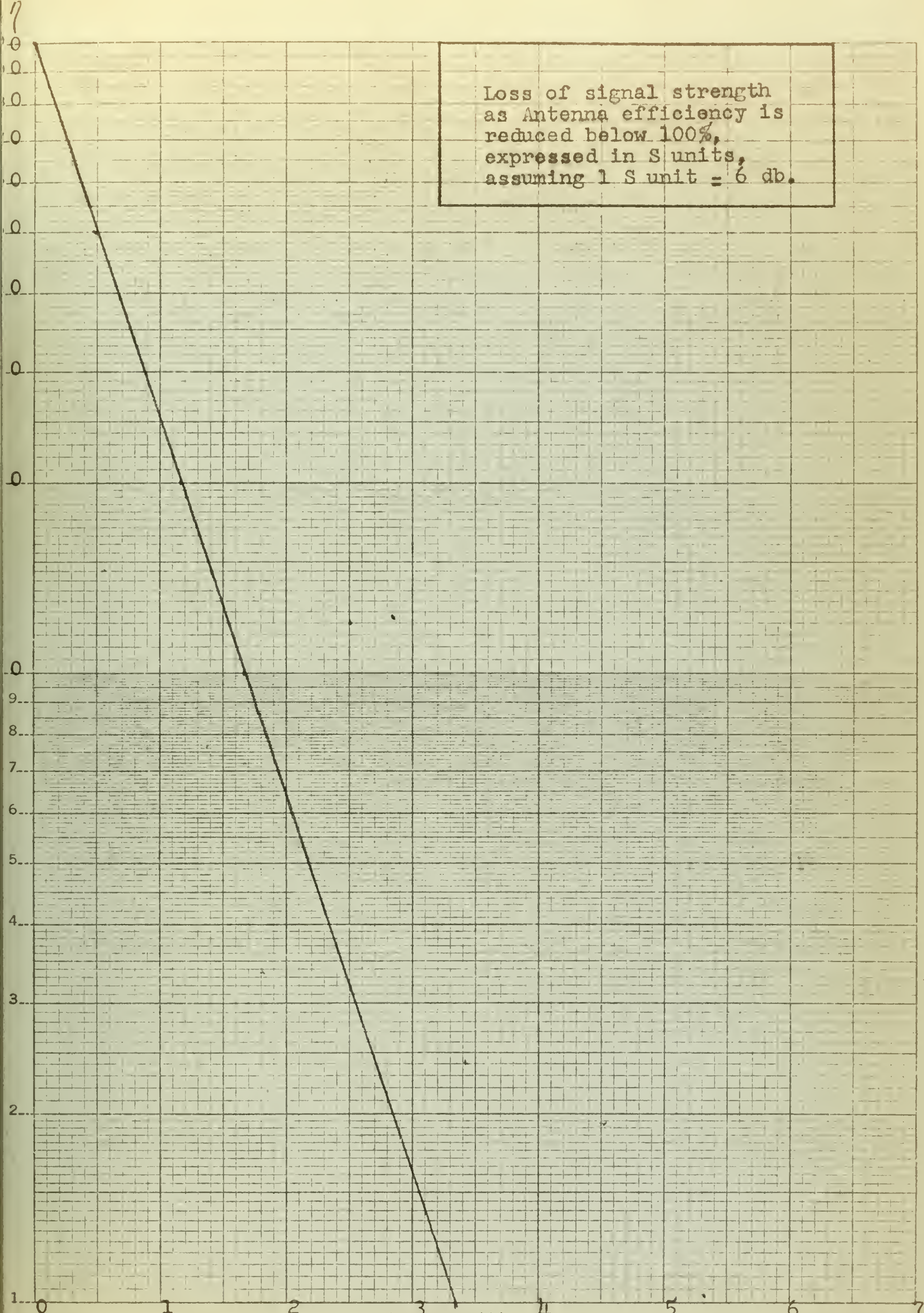

EQUIVALENT ADDED LINE LENGTH DUE TO PRESENCE OF TOP-LOADING
(where $X_c = 1/jwC_t$,
$Z_o = (L'/C')^{\frac{1}{2}}$
OR
ANTENNA CAPACITIVE REACTANCE VERSUS ANTENNA LENGTH FOR A SHORT VERTICAL GROUNDED WHIP, OR THE SECTION OF A LOADED ANTENNA ABOVE THE INDUCTOR
where $Z_o = 60 \ln 2h/a_c$
and $D = h\,360/\lambda$
1.0 X_c/Z_c
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
20
40
60
80
90
degrees
D

FIGURE 111

loss of signal strength as a function of loss of antenna efficiency is plotted in Figure IV, which shows the considerable effect that antenna efficiency has upon signal strength, or in inverse terms, where one is forced to utilize an antenna of less than 100% efficiency, the increase in transmitter power required. For example, if an operator using a 100 watt transmitter shifts from a fully efficient antenna to 10% efficiency, he must increase his transmitter, at considerable expense, to a kilowatt transmitter. It is economically important therefore to expend considerable thought and good design on antenna efficiency maximization.

We can express the efficiency as a simple ratio of resistances, provided that, referring to Figure I, the effect of the shunt impedances representing base insulator losses, and the series impedances representing transmission line losses can be neglected. The former will be significant where the base impedance of the antenna is greater than one-tenth the base insulator impedance. And the latter will be important, depending on the length of transmission line in use, whenever the standing wave ratio on the line becomes excessive. This will not occur



Loss of signal strength
as Antenna efficiency is
reduced below 100%,
expressed in S units,
assuming 1 S unit = 6 db.
(S units)

FIGURE IV

when the antenna is operated at its low impedance resistive mode, but will occur for a loaded antenna off this resonant frequency, or for an unloaded antenna. The latter situation mitigates against the system, long in use, of terminating a transmission line in an unloaded whip type antenna, and placing the compensating, or loading inductances at the transmitter end of the line. One can calculate the losses in, for example, a 200 foot length of RG/8U 52 ohm line terminated in a 35 foot, 1 ½ " diameter whip at 2.7 mcs. as being 2.9 db. It is interesting to note here that the SWR on such a line is merely X_c / Zo provided that Rr is less than 1/10 Zo, and Xc is greater than 10 Zo. To add to the line losses are the base insulator losses. Kandoian[12] has calculated for a 40 uuf, .001 power factor base insulator, the ratio of power lost to power radiated as approximately:

$$Pl/Pr \approx 1.25 / f^3 \text{ mc.} \qquad (12)$$

for the same 35' whip. At 1 megacycle the efficiency due to base loss alone is about 50%, while at 300 kcs. the efficiency is about 2 %.

Since we choose to discuss these antennas where the shunt impedances can be neglected, we can then write

the antenna efficiency as the ratio of radiation to loss plus radiation resistances. This is valid for a series network where the current through the circuit is a constant. It must be recognized that the current through a short antenna system is not limited to one path, and that the current leaving the top of a loading inductance may not be numerically equal to that entering the bottom. We will discuss the requisite correction for current distribution in the next section.

We have thus limited our discussion to the following loss resistances as affecting the system efficiency: radiation resistance, connection losses, inductor losses, and ground return resistance. The first we have already discussed, the second we shall assume minimized, and the third we shall discuss in the next section.

The evaluation of ground loss resistance is difficult. The author felt that an approximation would be satisfactory, since there were indications[13] that it was of the order of one-tenth the coil loss. Accordingly, the base impedance of the Baymobile antenna was measured over ground at approximately 20 ohms. The antenna was then placed in position on an automobile and the impedance again measured

with the automobile at the end of a long pier over the salt water of Monterey Bay. The reduction in base impedance, presumably equal to the ground return loss, was of the order of two ohms, and this value has been used throughout the calculations of Chapter II. It is of interest to note that Wagner [13] noted a whip resistive component of driving point impedance of 4-6 ohms where the radiation resistance expected was of the order of ½ ohm. The difference is believed to be the sum of R_g, R_c, and an increase in Rr due to automobile body return currents. This would confirm our estimate of the order of Rg as two ohms.

5. Inductor Losses - Apparent and Effective Q

If we have decided that the efficiency of a short antenna is the ratio of radiation resistance to loss resistance plus radiation resistance, and if it appears that the major component of loss resistance occurs in the inserted matching inductance, or loading coil, then it is of considerable importance to investigate the nature of the loss resistance of a coil. This is by no means a new field in the basic concepts involved.[2] First, a figure of merit, or Q for an inductance is defined as

the ratio of inductive reactance to loss resistance of the coil. In the case of our loading coil, it becomes primarily important to minimize the loss resistance value, rather than merely maintain a high Q. That is, we can minimize the loss resistance of our circuit by either maintaining a high Q, or reducing the value of inductance used. The parameters involved in designing a high Q coil are already set forth in the literature,[2,15] however, insufficient engineering emphasis has been placed, it is felt, on the importance of maintaining a low ratio of distributed to tuning capacitance. The following equations can be derived for the effect of distributed capacitance upon coil Q and effective inductance:[3]

$$Q_a = Q\,(1-m^2) = Q\,\frac{C}{C + Co} \qquad (13)$$

$$La = \frac{L}{1-m^2} = L\,\frac{(C + Co)}{C} \qquad (14)$$

$$Ra = \frac{R}{(1-m^2)^2} \qquad (15)$$

Where $M^2 = \frac{w^2}{{w_o}^2}$, w is the operating frequency, w_o the coil self resonant frequency, and C is the circuit series tuning capacitance. That is, if a coil is being

tuned by a capacitance of, as is the case of the BAYMOBILE commercial 4 mc. antenna, about 11 uufd., and has a distributed capacitance of 4 uufd, then its inductance is increased by the factor 15/11, its Q is reduced by 11/15 and its loss resistance is increased by $(15/11)^2$. But since we are tuning against a fixed capacitance of 11 uufd., the net effect is that a smaller coil is needed, and the loss resistance of the circuit only increased by the factor, $\frac{1}{1-m^2}$.

It would appear then, necessary to maintain a high Q, as high a tuning capacitance as possible, and as low a distributed capacitance as possible.

To illustrate, we tabulate in Figures VI, VII, VIII, and XVII, these constants as measured on several commercially available coils.

Having decided that a high Q is important, let us modify this concept by saying that the important factor is actually a minimum loss resistance referred to a current anti-node. For example, if a loading inductor is so placed that only half current flows through it, it consumes one-quarter loss power referred to the current anti-node and therefore its equivalent loss resistance

is one-quarter the coils a.c. loss resistance. That is the effective Q of that coil is four times the apparent Q as measured on a Q meter. The ratios (Kq) for the systems under discussion are shown in Figure II.

There are two methods of approximating this factor. Basically, we must determine the current distribution through the coil, square it, and take the reciprocal of the average of this square. When the loading inductor is lengthy and can be assumed to have some portion of a sinusoidal distribution, we write:

$$\frac{Q_{eff}}{Q_a} = \frac{Dc/57.2}{\int_0^{Dc/57.2} \cos^2 x \, dx} \qquad (16)$$

where

$$\int_0^x \cos^2 x \, dx = x/2 + \frac{\sin 2x}{4} \qquad (17)$$

This method is analytically justifiable. It is also possible to estimate the order of the factor by the empirical:

$$(Qeff/Qa)^2 \approx Io/Il \approx \frac{Ca + Ct + Cc}{Ca + Ct} \qquad (18)$$

6. Transmission Line Losses and Band-Pass

We have already discussed the case of losses incurred in a transmission line terminated in a whip type, unloaded antenna. When a short antenna is loaded and then operated at its resonant frequency, its base impedance is low and consists very largely of the loss resistances. Transmission lines are comercially readily available in characteristic impedances as low as 52 ohms. The SWR will then be, AT RESONANCE ONLY, at a minimum value or Zo/Rb. It might appear then that the losses will be relatively negligible. However, if an attempt is made, as is commonly practiced, and even recommended by some manufacturers (for example, VAARO) to terminate the line directly at the antenna base, and then trim the antenna until a resistive input occurs at the line input, the antenna will then be operated off-resonance by an amount dependent upon the line length, the mismatch, and circuit Q involved. The attendant line losses may no longer be negligible. This condition can be remedied by minimizing the line length, retuning the antenna with a series tuning circuit, re-matching at the transmitter when the antenna is operating at its self-resonant frequency (as measured

[illegible]

[illegible]

at the antenna base), manufacturing a low impedance line by paralleling several coaxial cables, or inserting a base matching section.[25]

It would appear that an antenna would have two operating modes when mis-matched: its self resonant frequency and a second frequency at which the input to the line is resistive. A picture of the response of an antenna to random noise is shown in Figure V.

A QUALITATIVE EXAMPLE OF THE TWO POSSIBLE MODES OF OPERATION OF A HIGH-Q ANTENNA TERMINATING A SHORT LENGTH OF MISMATCHED TRANSMISSION LINE ; ITS SELF-RESONANT FREQUENCY AND THE FREQUENCY AT WHICH THE SENDING END REACTANCE IS ZERO.

Land camera picture of an RBY sweeping 1oo kcs. either side of a Baymobile antenna terminating a 12.2 ohm line. The response is to random noise, R_b = 20 ohms , D_1 = 60°. f_0 = 4050 kcs.

FIGURE V

CHAPTER II - EFFICIENCY AND RESONANT FREQUENCY CALCULATIONS

1. Systems To Be Tested

In attempting to decide upon several systems to compare in efficiency it was felt that they should be representative systems, systems of the same order of fraction of a wavelength, and systems whose efficiencies would be expected to vary from poor to good, so that the results of poor engineering would be apparent. To obtain several systems to satisfy those requirements meant choosing an operating frequency where such systems were commercially available. This limited us to two choices: the 75 meter amateur band, and the small boat range near 2.5 mcs. Both systems are of the same order of a fraction of a wavelength, but three amateur systems were on hand, they were of a smaller length, and thus easier to handle, and more design literature was available.

As a result, the Master Mount system, the Mallard base-loaded, and the Baymobile were chosen, in addition to several representative helical designs, data for which were available. For equation confirmation purposes a helical was constructed with sixty-eight feet of wire,

and two 75 meter helicals were built, the first intended to surpass the commercial systems in use, and the second to show the order of improvement obtainable by increased wire size.

2. Methods of Calculation - Series Resonant Method

When the loading inductance is quite small compared to a wavelength, its inductance can be calculated by the equation:[8]

$$L(uh) = \frac{a_c^2 \, n^2}{15 \, a_c + 45 \, l_c} \qquad (19)$$

or may be measured on a Q meter. The capacitance of all elements above the top of the loading coil may be calculated from (9), and (10), and added. The resonant frequency of the antenna will then be the resonant frequency of this combination.

The efficiency of such a system will be the ratio of the radiation resistance as calculated by the equations of Figure II to the sum of the loss resistance as calculated by:

$$Rl = wLa \, / \, Q_{eff} \qquad (20)$$

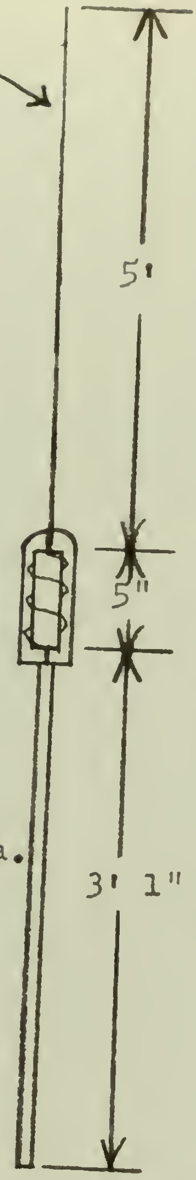
and the estimated ground return resistance.

One notes that a series circuit analysis lacks a high impedance input at 2f, that such a high impedance will occur at the self-resonant frequency of the coil, w_0.

Figures VI, VII, and VIII, are sample calculations. Since our very short antenna exhibits considerable reactance at frequencies below its quarter wave resonance point, and since we are inserting a lumped or distributed inductance in order to provide an approximately resistive driving point impedance, we have considered the circuit as a series resonant one. As such it will have an effective Q, that is the numerical ratio between reactance of the circuit and the circuit losses. As in any other circuit exhibiting such characteristics, there will be a pass-band determined by this circuit Q. It can be readily shown[19] that this pass-band will be f, the operating frequency divided by the circuit Q. These conditions, combined with an assumed pass-band, for amplitude modulation of 0-3500 cycles, sets an upper limit on the allowable circuit Q. This value of Q is about 200 f(mc). Applying this condition to a whip of 15 feet length, 2" diameter, and assuming a loading inductance Q of 600 as being the maximum possible, and loading our whip until

3/16" taper to 3/32"

C_a = 14.8 uuf.
C_s = 4 uuf
L_a = 85 uh. (meas.)
Q_a = 50 (est.)



Shield over a 4" x 1" coil, 123 turns #21
L_{calc} = 78 uh.

w_o = 13.3 mcs. without shield

3/8" dia.

$$R_r = .0046 D^2 = 3/4 \text{ ohm}$$

$$R_l = \frac{8\pi\ 85}{50 \times 1.1} \approx 38.6 \text{ ohms}$$

ESTIMATED EFFICIENCY : $\dfrac{3/4}{38.6 + 3/4 + 2} \sim 1.8\ \%$ (- 17.5 db)

CONSTRUCTIONAL AND ELECTRICAL DETAILS MASTER MOUNT
75 METER AMATEUR CENTER LOADED SYSTEM

FIGURE VI

3/8 " to 3/32" taper

C_a (calc.) = 24.7 uuf.
$L_{req'd}$ = 65 uh.

But coil range is:
42 - 56 uh.
So 18" of 5/8" dia.
brass extension added,
adding another 6 uuf.

Q_a (meas.) = 65

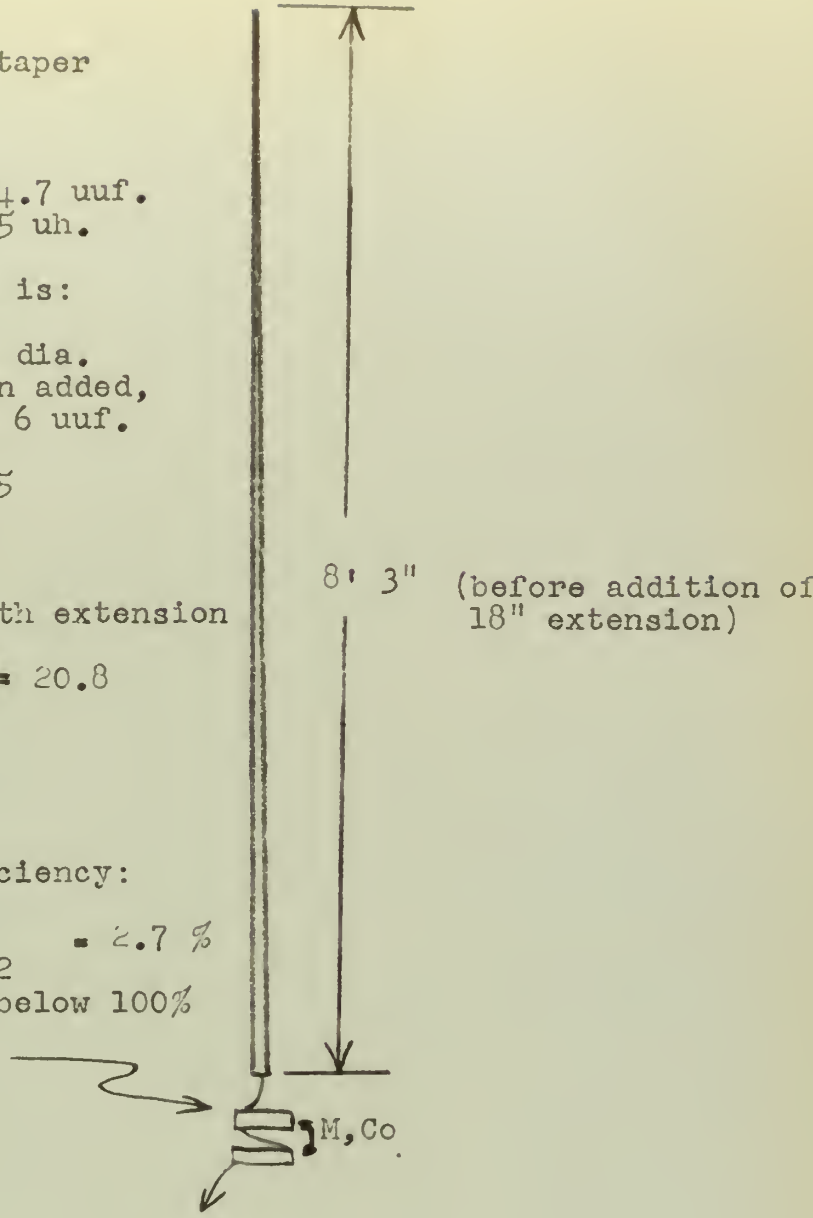
$R_r = .003\ D^2$
.64 ohms with extension

$R_l = \omega L_a/Q_{eff} = 20.8$
$R_g \approx 2$

Estimated efficiency:

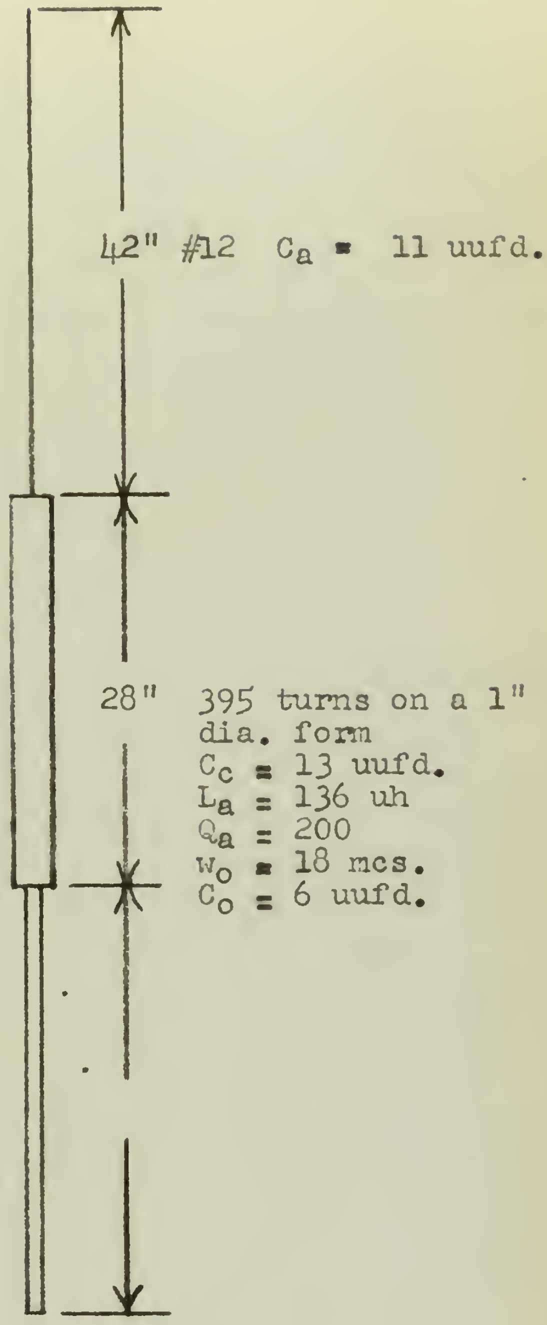
$$= \frac{.64}{20.8 + .64 + 2} = 2.7\ \%$$

(- 15.7 db. below 100%



CONSTRUCTIONAL AND ELECTRICAL DETAILS MALLARD "HI-Q 75"
75 METER AMATEUR BASE- LOADED SYSTEM

FIGURE VII



$$R_r = .0046\, D^2 = .84 \text{ ohms}$$

$$R_l = \frac{2\pi \times 4 \times 136}{1.4 \times 200} = 12.2 \text{ ohms}$$

Efficiency, neglecting other losses : 6.5 %

ESTIMATED EFFICIENCY : ($R_g = 2$) $\sim$ 5.6 % (-12.5 db)

CONSTRUCTIONAL AND ELECTRICAL DETAILS BAYMOBILE
75 METER SYSTEM FOR AMATEUR MOBILE USE

FIGURE VIII

its radiation resistance is the maximum possible, that is:

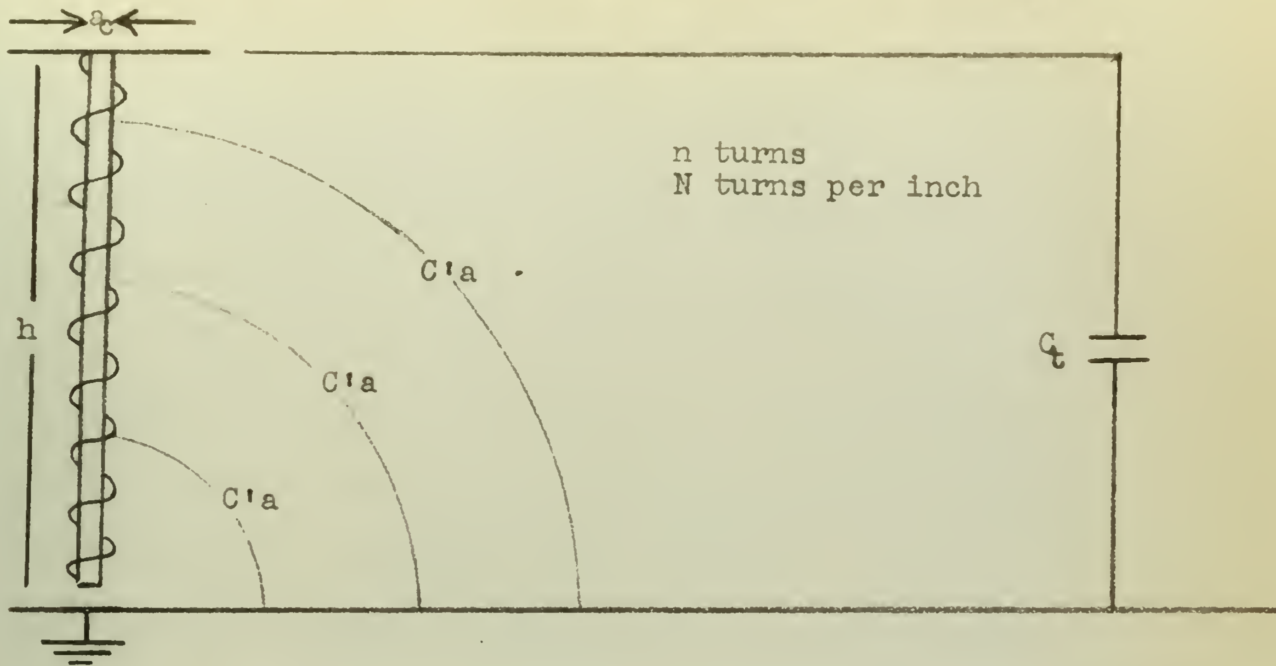
R_r max = .00082 $\lambda^2 f^2$ (mc.), we can insert enough radiation resistance into our system to lower the minimum radiating frequency from 600/200 or 3 mcs. to 2 mc.

This indicates that we can not operate such a whip below 2 mcs. and still obtain a 3500 cycle passband without intentionally loading our system, thereby reducing its efficiency even further.

2. Distributed Transmission Line Method

When the loading inductor is short in length, and the series resonant method is used, the factor most seriously preventing maximum antenna efficiency is coil distributed capacitance. If one attempts to avoid such distributed capacitance by lengthening the inductor, an increasing discrepancy between actual and calculated resonant frequency will be noted. At such a point it becomes necessary to utilize another method. Suppose, referring to Figure IX we consider our antenna loading coil as a long inductance with a certain "capacitance to ground" as determined by (9). Imagine this capacitance as made up of many small capacitors terminated every

DISTRIBUTED TRANSMISSION LINE ANALOGY TO A SHORT HELICAL ANTENNA TO OBTAIN DESIGN EQUATIONS AND $V_{w/c}$



1) $L = \dfrac{.2\, a_c^2\, n^2}{3\, a_c + 9 \times 12h} = (12h \gg a_c) = \dfrac{.2\, a_c^2 n^2}{108\, h}$

$L' = L/h = a_c^2 n^2 / 540\, h^2$ uh/ft

2) $C = \dfrac{17h}{\ln 24h/a_c - 1} = (h/d = 10)\ 3.78\ h$

$C' = C/h = 3.78$ uuf/ft

3) $Z_o = (L'/C')^{\frac{1}{2}} = \dfrac{n\, a_c\, 1000}{23.2\ h\ (3.78)^{\frac{1}{2}}} = 267\ N\ a_c$ ohms

4) $Bl = w(L'C')^{\frac{1}{2}}\, h = pi/2$

$f_{\lambda/4} = 250 / (L'C')^{\frac{1}{2}}\, h$ mcs.

5) $f_{\lambda/4} = \dfrac{250}{\dfrac{n\, a_c}{23.3\ h} \times 1.95 \times h} = 2980 / n\, a_c$

But $\pi\, n\, a_c = 12\ l_w$

So $f_{\lambda/4} = 2980\, \pi / l_w\, 12 = 783 / l_w$

6) But in free space $f_{\lambda/4} = 246 / l$ so $V_{w/c} = 783/246 = \boxed{3.18}$

FIGURE IX

foot of length of the inductor. The resulting configuration is immediately recognized as an unbalanced distributed transmission line. One can apply the equations of a transmission line to the situation. The line will show a resistive input where its length in degrees:[5]

$$Bl = w\,(L'C')^{\frac{1}{2}} \times 57.2 \qquad (21)$$

added to the length in degrees of the antenna top section and any capacitance loading used as determined from Figure III equals ninety degrees. A second resonant-high impedance point will be noted at 180°.

The current distribution will be sinusoidal.[12] Figure IX includes the approximating equations.

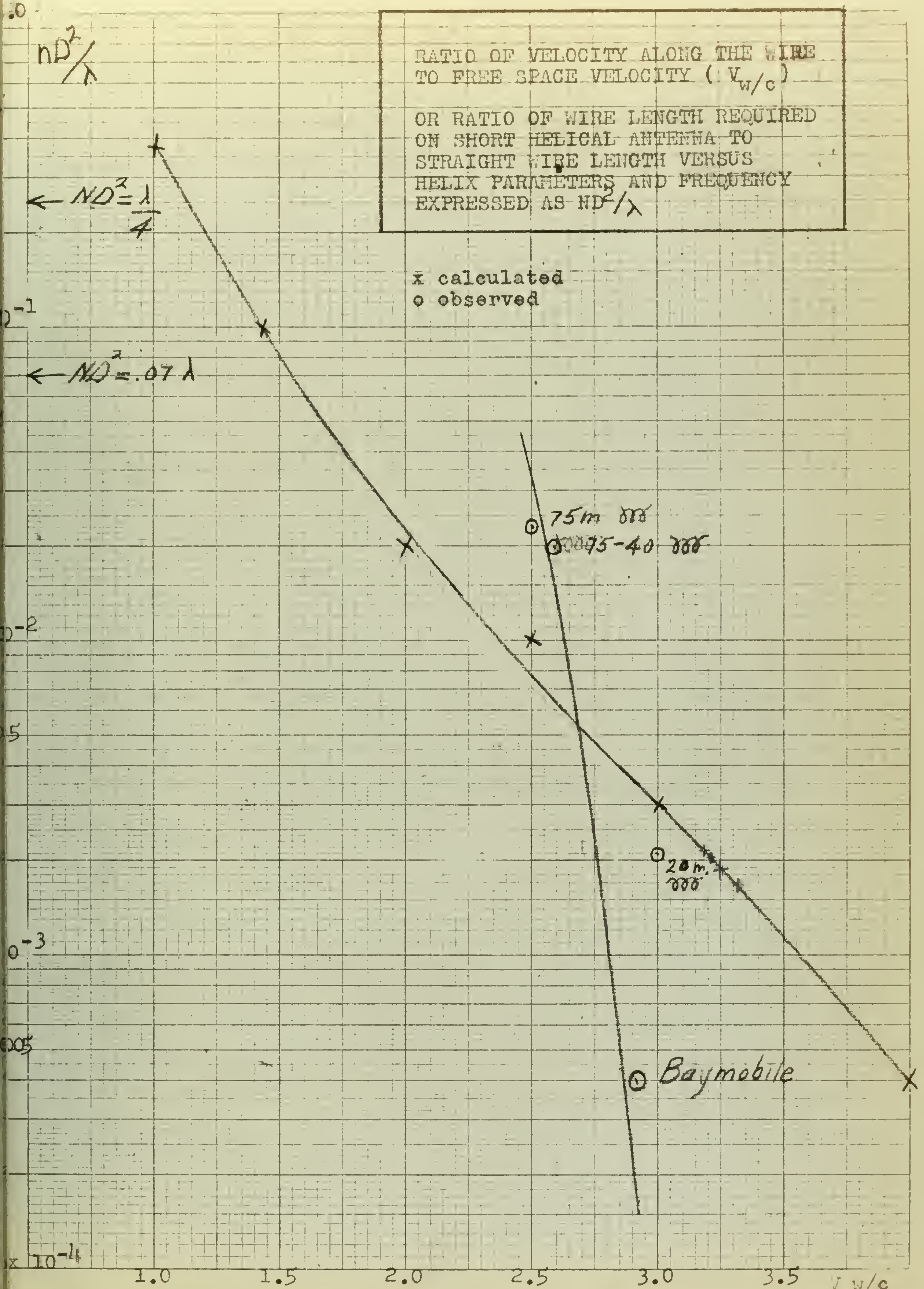
4. Distributed Loading - The Helical Antenna

Suppose we continue our transition from the lumped loading inductor to a lengthy coil, and carry our transition to the extreme, that is make the entire antenna a loading coil. We now recognize the resulting configuration as a "distributed loading" system, long in use, or a helical[20,21] antenna. Kandoian[12] has recently published a paper on the subject and includes several equations of considerable usefulness. Kraus[14] has done considerable work with helical antennas radiating in the

axial mode, that is where the length of wire used is several wavelengths long, above thirty megacycles. Our antenna is so short, in terms of a wavelength, and its diameter is so small in terms of its length that it can be considered to be radiating in the "normal" [14] mode, i.e. vertically polarized. There are many design parameters involved, but there is one simplifying concept that we shall use. We use Kandoian's $V_{w/c}$, the ratio of apparent velocity along the wire to free-space velocity as merely the factor by which one increases the length of wire one would use in free space to the length of wire wound on the helix. When the helix diameter is such that:

$$Nd^2 > \lambda/4 \qquad (22)$$

this ratio is one,[12] but for helices wound on a long thin coil form ($\pi h/d \sim 100$) it is about 2.8. Figure X shows the plot of the variation obtained experimentally compared to the calculated value, and Figure IX continues the development of the transmission line analogy to show that the maximum expected value of $V_{w/c}$ is about 3.18. For design purposes one may use 3.0 as an initial approximation, and since the length in free space is:[8]



RATIO OF VELOCITY ALONG THE WIRE TO FREE SPACE VELOCITY ($V_{w/c}$)
OR RATIO OF WIRE LENGTH REQUIRED ON SHORT HELICAL ANTENNA TO STRAIGHT WIRE LENGTH VERSUS HELIX PARAMETERS AND FREQUENCY EXPRESSED AS ND^2/λ
x calculated
o observed
nD^2/λ
$\leftarrow ND^2 = \frac{\lambda}{4}$
$\leftarrow ND^2 = .07\lambda$
75m
75-40
20m.
Baymobile
1.0
1.5
2.0
2.5
3.0
3.5
V w/c

FIGURE X

$$L_{\lambda/4} = \frac{246}{f_{mc}} \qquad (23)$$

then:

$$l_w \lessapprox \frac{780}{f_{mc}} \qquad (24)$$

Kandoian[12] also writes an equation for the ratio of power lost to power radiated. This corresponds to evaluating R_L from (20) AND OMITS CONSIDERATION of dielectric, ground return, and connection and line losses. Figure XI is a plot of this maximum expected efficiency. Figures XII, XIII, and XIV are sample calculations, and Figure XV is an example of the correlation obtainable in the borderline case.

5. Loop Radiation Resistance and Effective Height

Having considered a simplification of the short helical antenna design problem, one might here include for comparison the equations relating the effective height and radiation resistance of a loop antenna (a very short, large diameter helix) to its dimensions. One can develop relatively simply the equation for the terminal voltage of a loop antenna as a receiving antenna to be:

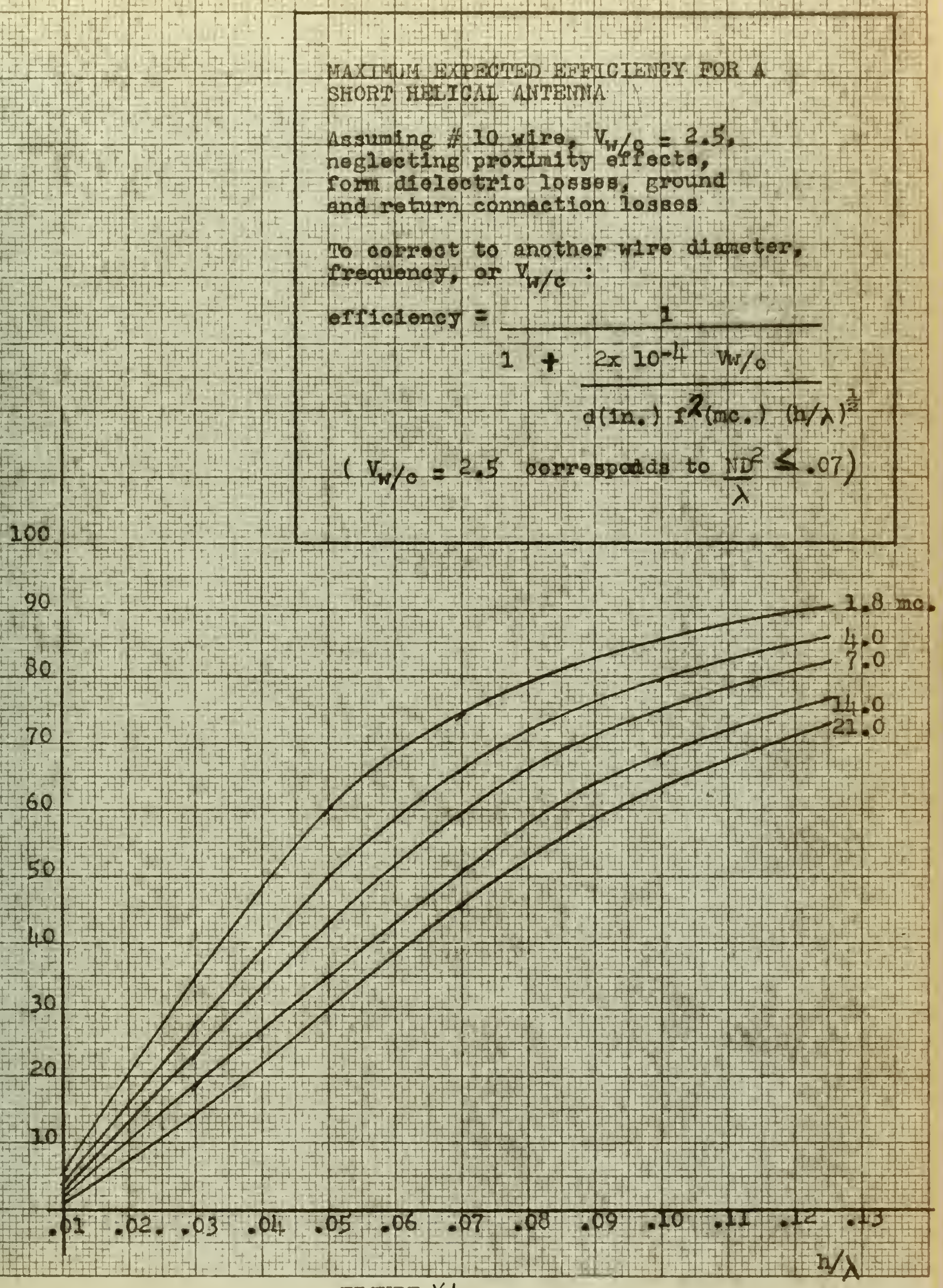

MAXIMUM EXPECTED EFFICIENCY FOR A SHORT HELICAL ANTENNA
Assuming # 10 wire, $V_{w/c} = 2.5$, neglecting proximity effects, form dielectric losses, ground and return connection losses
To correct to another wire diameter, frequency, or $V_{w/c}$:
efficiency = $\dfrac{1}{1 + \dfrac{2x\,10^{-4}\ Vw/c}{d(in.)\ f^2(mc.)\ (h/\lambda)^{\frac{1}{2}}}}$
($V_{w/c} = 2.5$ corresponds to $\frac{ND^2}{\lambda} \leq .07$)
100
90
80
70
60
50
40
30
20
10
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
.13
h/λ
1.8 mc.
4.0
7.0
14.0
21.0

FIGURE XI

CONSTRUCTIONAL AND ELECTRICAL DETAILS W3HWT 20METER MOBILE HELICAL ANTENNA

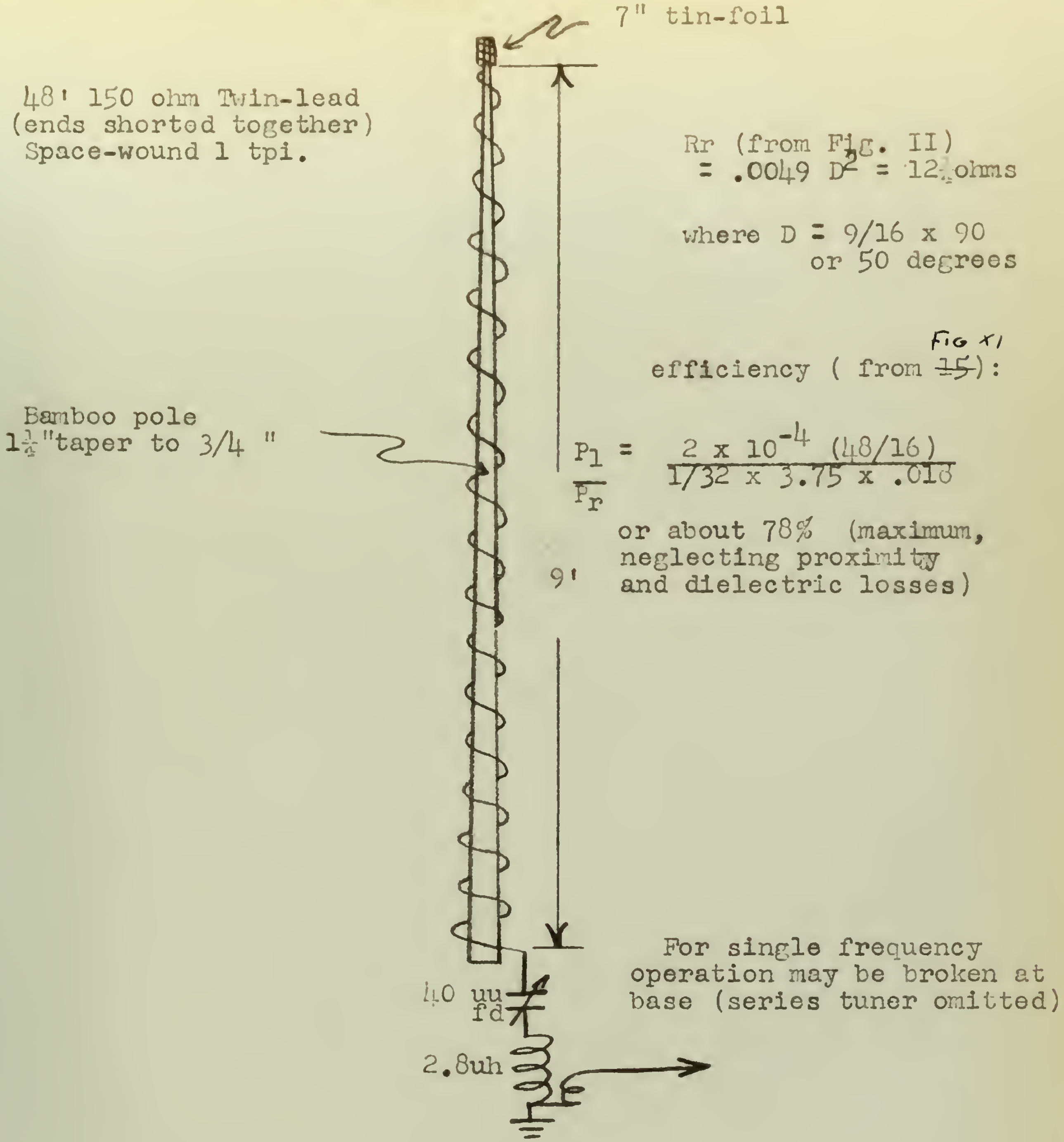
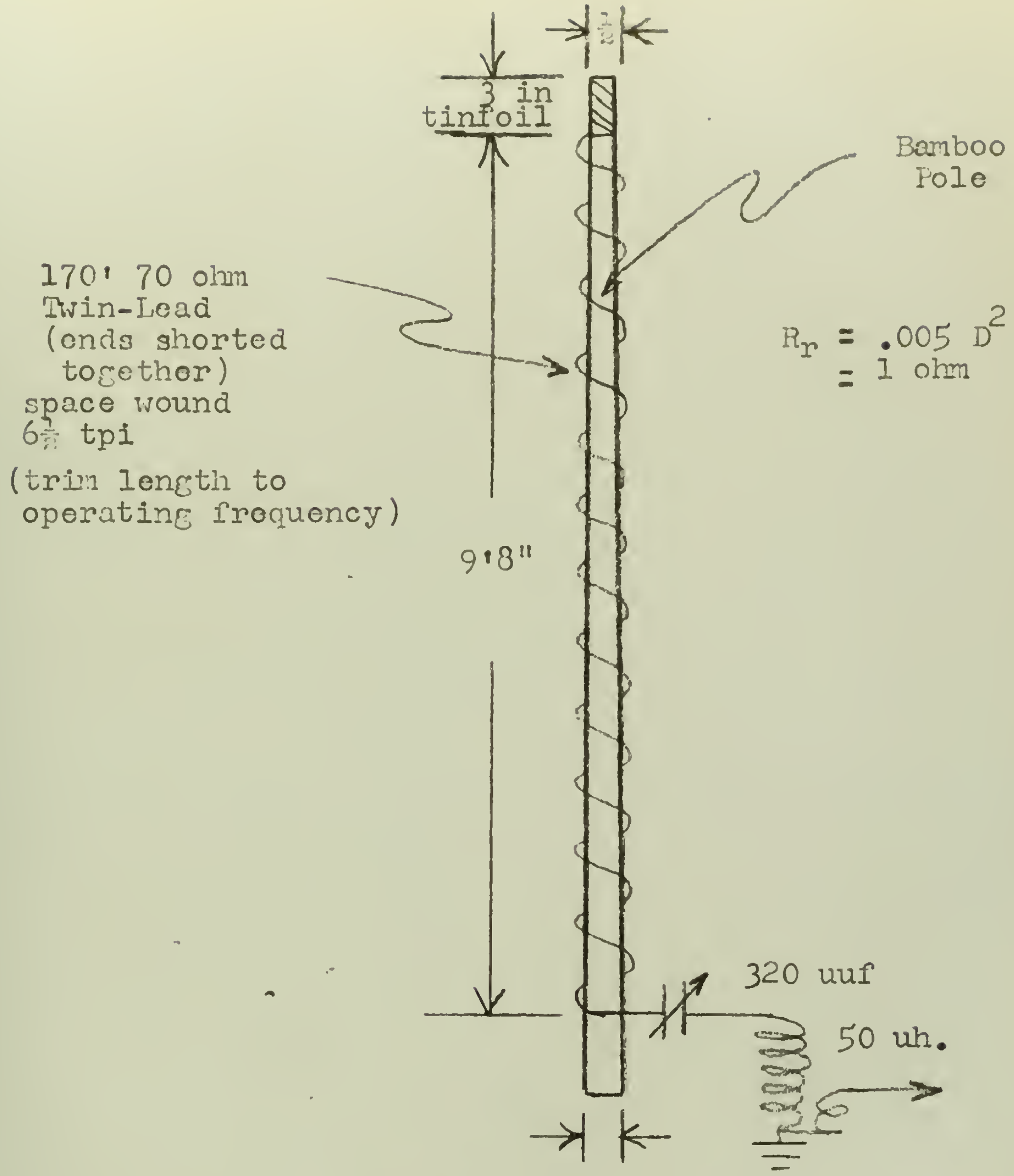


Figure XII

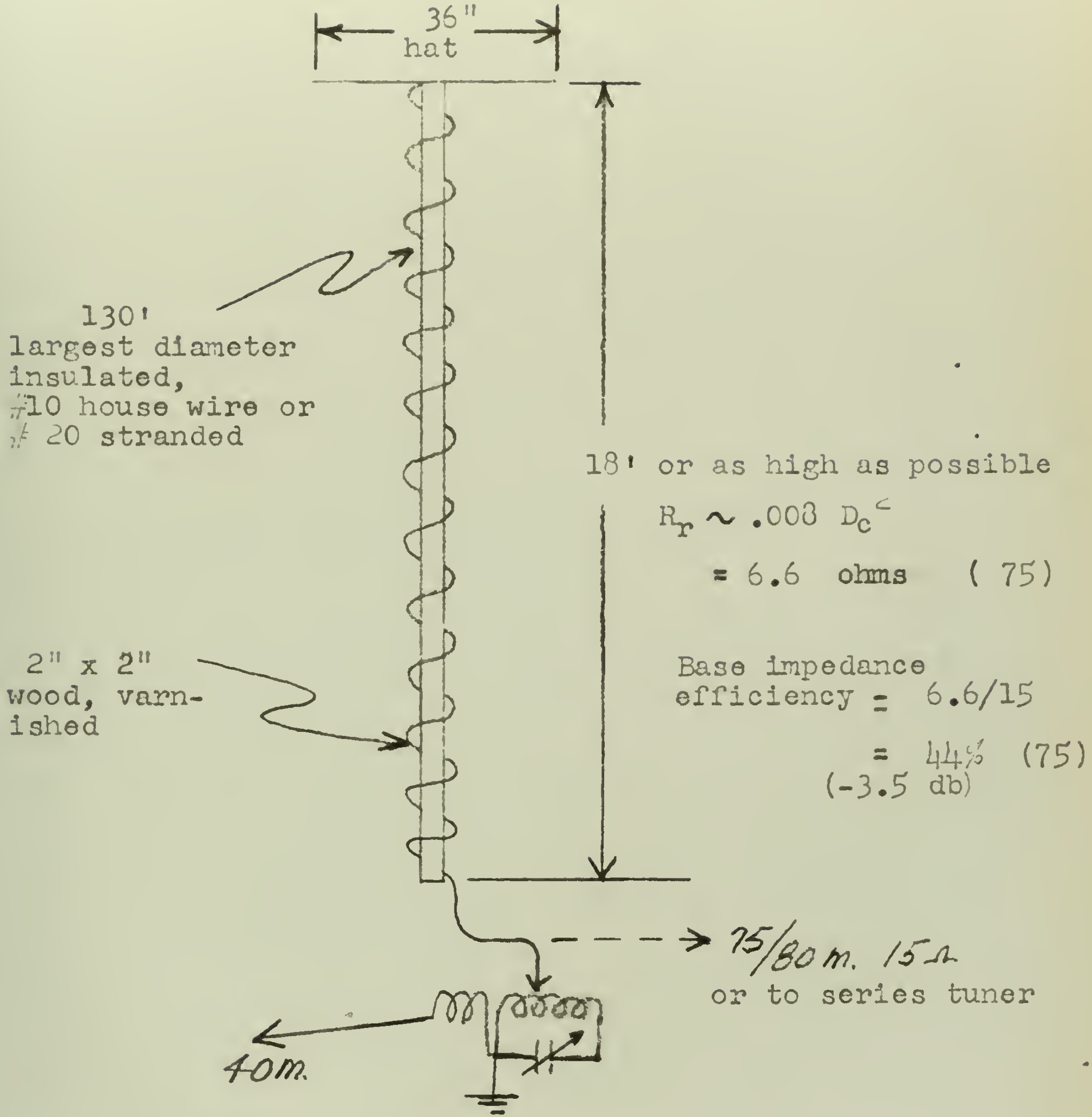


From Figure XI, efficiency will be 19% max.

Estimated actual efficiency : 10%

CONSTRUCTIONAL AND ELECTRICAL DETAILS W3HWT 75 METER MOBILE HELICAL SHORT ANTENNA

FIGURE XIII



CONSTRUCTIONAL AND ELECTRICAL DETAILS W3HMT/ W2FYT
FIXED 80 AND 40 METER SHORT HELICAL ANTENNA

FIGURE XIV

THE BORDERLINE CASE - AN EXAMPLE OF THE CLOSE CORRELATION OBTAINABLE FROM THE LUMPED LOAD AND DISTRIBUTED TRANSMISSION LINE ANALYSES OF A CLOSE-WOUND LENGTHY LOADING COIL- USING THE BAYMOBILE ANTENNA AS AN EXAMPLE

a) As a lumped circuit series resonant:

La = 136 uh. (extrapolated from measurements)
Ca = 11 uuf (calculated from (9)

$$f_{90} = \frac{1}{2\pi (LC)^{\frac{1}{2}}} = 4100 \text{ kcs. } (4050 \text{ measured})$$

b) As a distributed transmission line:

1) Calculate $Xca = \dfrac{1}{2\pi 4.05 \times 11 \times 10^{-6}} = 3570$

2) From Figure III, with Xc = 3570,

and $Zo = (L/Cc)^{\frac{1}{2}} = 113/13)^{\frac{1}{2}} \times 1000 = 2950$
Xc/Zo = 1.20 representing 39.6 degrees in top section of antenna

3) To find the length of the coil in degrees:

$$Bl = 2\pi f\ (LC)^{\frac{1}{2}} = 2\pi \times 4.05 \times 10^{6}\ (113 \times 13)^{\frac{1}{2}} \times 57.2$$
$$= 56 \text{ degrees in the coil}$$

4) The sum should be 90 degrees but is actually 39.6 + 56 or 95.6, a correlation of 6 %, within the precision of the equations and measuring equipment used.

FIGURE XV

$$e_r = \frac{2\pi An}{\lambda} \quad E_{max} \cos\theta \quad \sin wt \qquad (25)$$

From which the effective height is apparently:

$$h_{eff} = \frac{2\pi An}{\lambda} \qquad (26)$$

Considering the radiation resistance of a current carrying short wire to be[14]:

$$R_r = 80\,\pi^2\,(\,l/\lambda\,)^2 \qquad (27)$$

and considering "l" to correspond to the effective height, the radiation resistance becomes:

$$R_r = 80 \times 4 \times \pi^4 \quad (An/\lambda^2\,)^2$$

$$= 31{,}200 \quad (\,nA/\lambda^2\,)^2 \qquad (28)$$

This equation is confirmed in Terman.[2]

Noting that:

$$l_w = \pi\, a_c\, n \qquad (29)$$

and $A = \dfrac{\pi\, a_c{}^2}{4}$ (30)

(28) becomes :

$$R_r = 1950\,\frac{l_w{}^2\, a_c{}^2}{\lambda^4} = 1950\left(\frac{l_w}{\lambda}\right)^2\left(\frac{a_c}{\lambda}\right)^2 \qquad (31)$$

For example, winding the same 160' of wire used in our helices on a 16.3 ' diameter loop would result in a radiation resistance of four ohms in a normal[14] mode, at four mcs.

6. Base Impedance Method

Probably one of the more reliable methods available is the base impedance method whereby we measure the base impedance of the antenna, calculate from Figure II the radiation resistance, and divide the second by the first. Figure XVI gives the measured base impedance characteristics of the antennas tested.

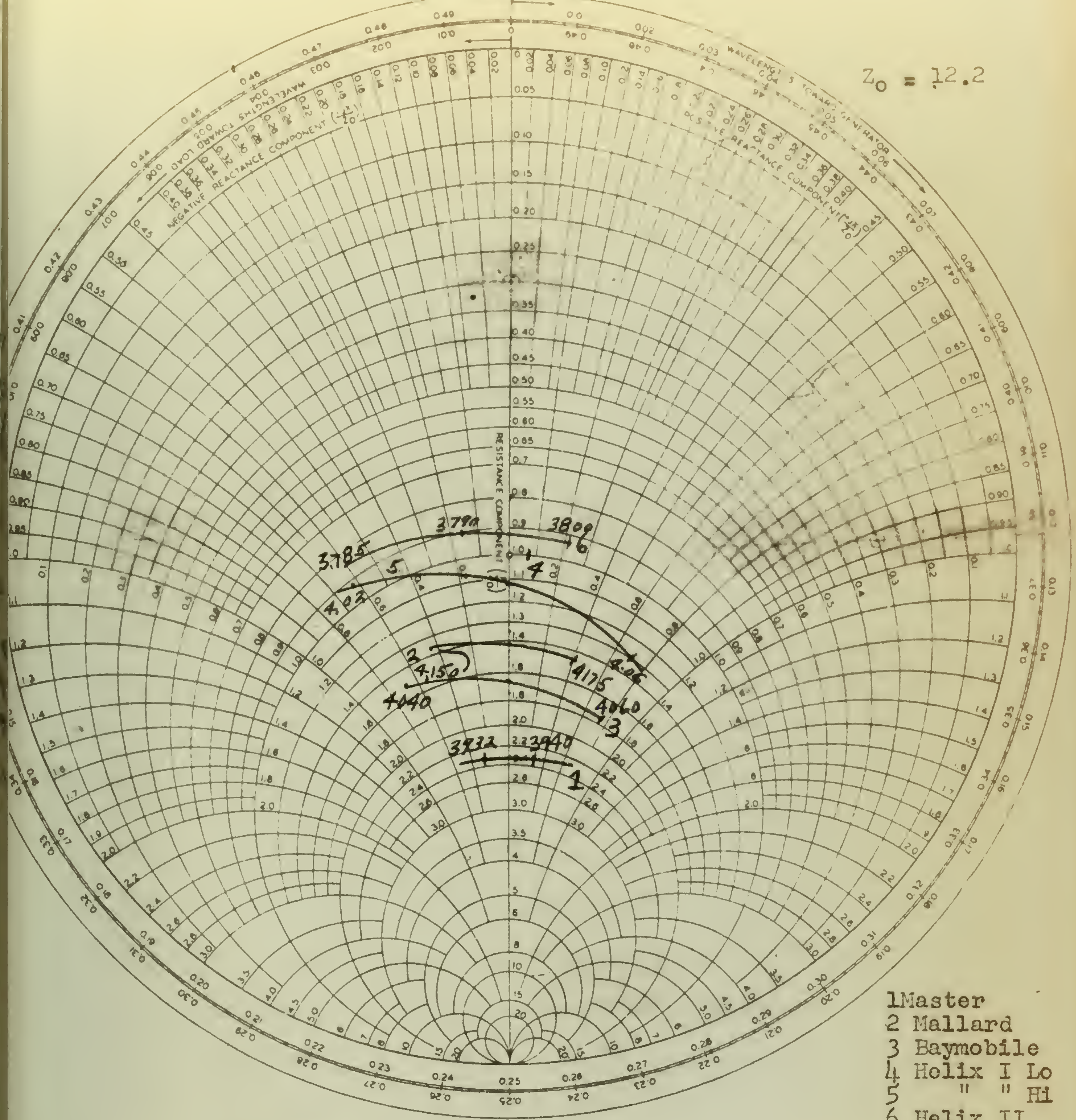
7. Summary of Expected Efficiencies

	Series Method	Base impedance	Helical
Master Mount	1.8 %	2.68 %	
Mallard	2.7 %	3.7 %	
Baymobile	5.6 %	4.1 %	
Helical I	6.66 % *	6.8 %	24 % max
Helical II		7.75 %	36 % max
8.3 Mcs. Helical	28.1 % *	36 %	48 % max

8. Figure of Merit

To anyone familiar with the workings of Nature's laws the fact that a natural limitation placed upon an

* Obtained by winding the helix in three sections, meas- the Q of each section at f_o , its L_a, calculating $r_{a.c.}$, adding for the three sections and dividing by two to find R_l eff; thence calculating R_r and thus the efficiency.



BASE IMPEDANCE CHARACTERISTICS OF TEST ANTENNAS

FIGURE XVI~~I~~

engineers attempts are independent of the method of approach, would come as no surprise. In the short antenna case, for example one notices that as a loading inductance is moved from the base position towards a higher position in order to increase the radiation resistance of a system, a larger inductance is required with apparently greater losses, but if this coil is made long with respect to its diameter in order to limit distributed capacitance, one departs from the maximum Q configuration. Thus it would appear that the net effect of so many factors tending towards opposite directions might be to place a limit on the obtainable efficiency that is independent of configuration.

One must here admit that the use of top-loading produces undoubtedly beneficial effects [15,8]; particularly when one so places such loading well above the loading coil so as to obtain the maximum increase in current distribution and the minimum increase in distributed capacitance across the coil used. But using such top-loading (in effect) requires making the antenna physically larger and thus, if we desire to evaluate a figure of merit for comparable systems, we must not consider such loading as

a factor.

Our antenna efficiency is roughly proportional to the effective Q of the coil, the radiation resistance -current distribution factor, a factor representing the fact that for a given amount of effort, one can manufacture a coil of higher Q for a lesser inductance, and inversely as the inductance required. We shall assume that such Q increases inversely as the square - root of the inductance required. Thus one can build a coil of Q = 141 at 50 uh., for the same amount of effort as a coil of 100 uh and Q = 100.

For our figure of merit we merely take the product of these factors: (see Figure II)

Base -loaded figure of merit $= .003 \times 1. \times 2 \times (2)^{\frac{1}{2}}$

$= .0085$

Center loaded figure of merit

$= .0046 \times 1.4 \times (1) \times (1)^{\frac{1}{2}}$

$= .00644$

Helical Figure of Merit $= .005 \times 2 \times (1) \times (1)^{\frac{1}{2}}$

$= .0100$

That these figures of merit are all of the same magnitude indicates that no one system is obviously superior to any other.

CHAPTER III MEASURED EFFICIENCIES

1. Measuring Technique

There is one factor in favor of an operator attempting to operate a transmitter in the medium and high frequency region up to several megacycles: the tremendous potentialities of one radiated watt. For example (Appendix) the calculated field strength at one mile per square root of radiated watts is 1400 microvolts/meter. This would induce an S 9 signal in a vertical quarter wavelength at four megacycles at a distance of about 16 miles.

To attempt to measure the efficiency of the antennas under measurement was basically a problem of measuring the field strength at one mile, calculating the radiated power therefrom, and taking the ratio of this power to the power input to the antenna.

The antennas were mounted on the west end of the Electronics Laboratory Butler hut, a low impedance line made of four paralleled 25' lengths of RG 59/ U run from the antenna base to the Receiver Laboratory where a GR 916A impedance bridge was used to measure the line input impedance, an LP signal generator used as a source, and

a TCS transmitter used as a driving source in the 3.5 mcs., to 4 mcs. amateur band operating as W2LHB/6 with permission of the Superintendent.

To obtain the line characteristic impedance open and shorted impedances were obtained and the line thus measured at 12.2 ohms instead of the 52/4 ohms expected.

2. Results of Measurements

Field strengths were measured by Lt. John T. Geary, USN, at a point one mile from the transmitting site with an AN/PRM 1 serial 74 Field Intensity meter. Transmitter output power was in all cases held to 16.5 watts. The most serious uncontrollable factor in the measurement chain was the directivity of the antenna, mounted as it was on an unsymmetrical ground plane. Indications were (Figure XIX)that its pattern would be directive along the length of the Butler Hut, and that, at some 45^{o} from that centerline, it might be back to the average power level. Since the change in conductivity towards the beach precluded a point in that direction, the monitoring point was chosen near the east end of the Monterey Polo Grounds, one mile distant. The measurement results were:

[illegible]

[illegible]

[illegible]

[illegible]

	Field Intensity	P_r	Efficiency
Mallard	1000 uv/m	.51	3.1 %
Master Mount	660	.22	1.33 %
Baymobile	1350	.93	5.64 %
Helix I (#15) *	1500	1.15	7 %
Helix II (#10)*	1670	1.42	8.6 %

The only serious discrepancy between the calculated and measured efficiencies was in the Master Mount case, due to the inability to precisely measure the coil Q with the shield in place.

* Corrected from 3.79 mcs to 4.0 mcs by the factor $(4.0/3.79)^{3/2}$, representing a decrease of loss resistance by the frequency ratio to the first power and an increase in radiation resistance by the square of that factor, the sum of the powers being three. Taking the square root of the voltage ratio results in a net field strength correction power of three-halves.

CHAPTER IV CONCLUSIONS

1. Tabulation of Calculated and Measured Radiation Efficiencies

	Calculated	Measured
Master Mount	1.8 to 2.68 %	1.33 %
Mallard	2.7 to 3.7 %	3.1 %
Baymobile	4.1 to 5.6 %	5.64 %
Helix I	6.66 to 6.8 %	7 %
Helix II	7.75 %	8.6 %

2. Recommended Design Procedure

In the design of a short antenna, as in any electronics problem, there are two aspects to be considered: the electrical and mechanical design considerations. Since we are discussing an inefficient short antenna, it must be assumed that some mechanical limitation has mitigated against use of a longer, more efficient system. We can, therefore, only discuss the electrical design factors here.

One should first decide the maximum height and degree of top-loading possible. From equation (24) the length of wire on the helix can be approximated. If top-loading is to be used, Figure III will give the

number of degrees in the top-load, from which the number of degrees in the helix is obtainable by subtraction. Next the form and wire diameters are chosen as the maximum possible. If top-loading is used, it will be most effective working above a high characteristic impedance helix, so the diameter and turns per inch are maximized. One can then calculate the length of winding of such a helix, and complete the height to the design value with heavy wire or tubing, recalculating the wire length after calculating the number of equivalent degrees in such a top-section whip, or trimming to the design frequency with a grid-dip meter. Should the helix length become almost the full length available, one has the alternate method available of using no top-section, but attempting to "fatten" the sinusoidal distribution, with attendant radiation resistance increase, by tapering the characteristic impedance from a high to a low value by increasing the spacing between turns as the helix top is approached.

In attempting to decide the type of termination to be used, one can consider perhaps three general cases: a direct termination, matched or unmatched, a series

tuning arrangement for re-tuning the antenna system to maintain a resistive termination to the transmission line, or attempting to calculate a length of mis-matched transmission line that would maintain, for a given Q and mis-match, a resistive INPUT. One can only indicate here the solutions. In the first case, a matched line can be constructed by paralleling several lines. Maximum efficiency is only achieved at the resonant frequency of the antenna. The series tuning arrangement requires remote tuning, and the third requires a Smith chart. Kandoian[12] has noted equations for the tap point on a helical antenna, the most useful being:

$$R_{tap} = \frac{Z_o^2 \sin^2 \theta}{R_b} \tag{32}$$

3. The author concludes that:

a) The calculation of radiation efficiencies by the demonstrated techniques are valid within the accepted precision of short antenna design

b) That all systems of loading a short antenna considered are inherently as good as any other with two exceptions:

1) the unloaded antenna terminating a coaxial cable is a distinctly inferior system due to excessive line and base insulator losses.

2) Capacity loading is similar to a physical lengthening of the antenna in that it is just as physically difficult to achieve and causes the same beneficial results. Further, that section of the antenna above the loading inductor can be treated as a capacity top-load.

c) That the difference between systems is the susceptibility to engineering error of the system. That is, lumped inductors, while inherently of a higher Q, are more susceptible to distributed capacitance losses.

d) That system having minimum susceptibility to engineering error is the helical or "distributed loading" system. The ratio of efficiency to care required in construction is highest here.

e) That a given top-loading section represents the greatest addition in length when terminating a high impedance helix. This high impedance is achieved when the diameter of winding and the turns per inch are the greatest possible.

f) That the design equation for a helix representing a given number of degrees of line at a given frequency is approximately:

$$l_w = \frac{8.7\, D_c}{f(mc)} \quad \text{where } D_c \text{ is the number of degrees desired in the helix} \qquad (33)$$

provided the ratio of h/a_c is great, the dimensions being of the order of a short whip.

g) That Nature recognizes no change in her laws due to a change in terminology as one proceeds from a loop of many turns, through lumped loading system to a distributed loading system, to a short helix, and continues towards a single wire or whip. All systems obey the same laws. It is merely a matter of convenience that we use different design equations.

h) That a loaded system is inherently, for the lumped loading system a one frequency system, and for a helix, a harmonic system.

i) That it is of importance that a high Q antenna be operated at its self-resonant frequency, and that any re-matching necessary due to line mis-match be performed at the antenna base, or that a low impedance line be made up by paralleling coaxial cables as one would parallel resistors.

j) That the ground conductivity measurement procedure as prescribed [5,17] gives valid results.

k) That the top third of a helical antenna, since it is a low impedance line if tapered, can be replaced by a whip section of as large diameter as possible, and that the helix below it be of constant diameter and turns per inch, both as great as possible for the maximum diameter wire used.

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APPENDIX

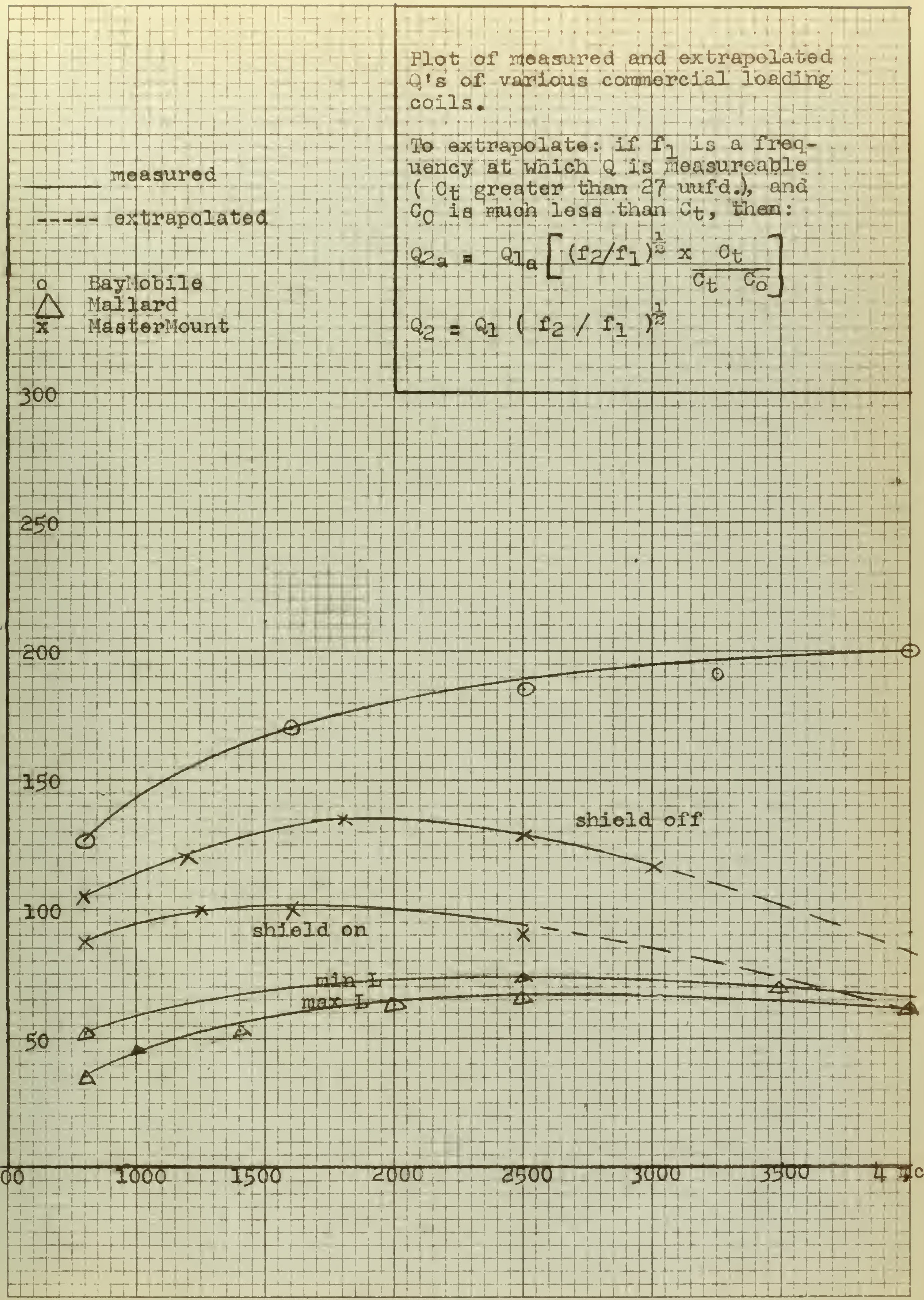

Plot of measured and extrapolated Q's of various commercial loading coils.
To extrapolate: if f_1 is a frequency at which Q is measureable (C_t greater than 27 uufd.), and C_0 is much less than C_t, then:
$Q_{2a} = Q_{1a} \left[(f_2/f_1)^{\frac{1}{2}} \times \frac{C_t}{C_t \quad C_o} \right]$
$Q_2 = Q_1 (f_2 / f_1)^{\frac{1}{2}}$
measured
----- extrapolated
o BayMobile
△ Mallard
x MasterMount
shield off
shield on
min L
max L
300
250
200
150
100
50
500
1000
1500
2000
2500
3000
3500
4 Kcs

Figure XVII

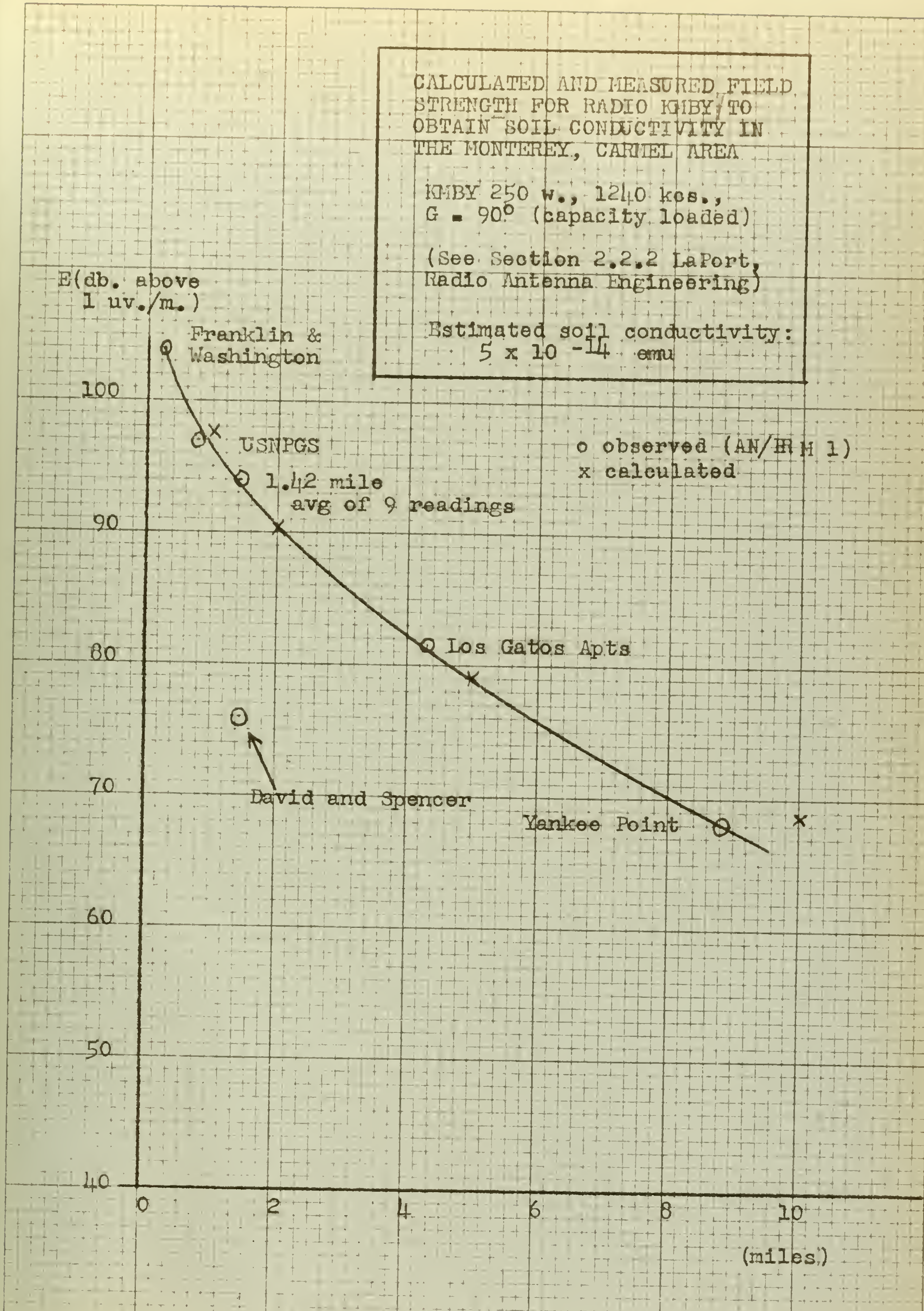
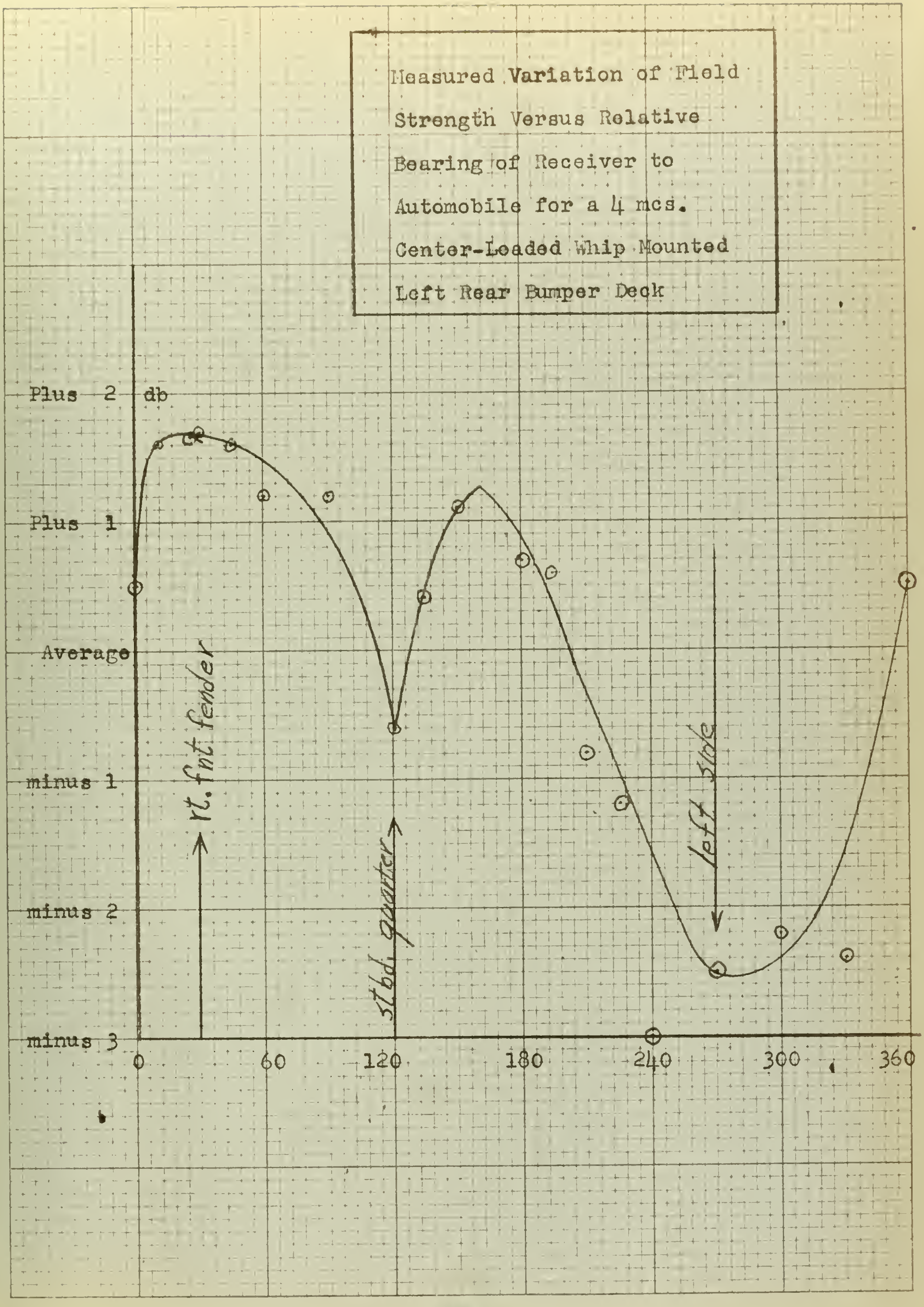


FIGURE XVIII



Measured Variation of Field
Strength Versus Relative
Bearing of Receiver to
Automobile for a 4 mcs.
Center-Loaded Whip Mounted
Left Rear Bumper Deck
Plus 2 db
Plus 1
Average
minus 1
minus 2
minus 3
0
60
120
180
240
300
360
rt. fnt fender
stbd. quarter
left side

FIGURE XIX

CALCULATION OF FIELD STRENGTH AT ONE MILE FOR ONE WATT AT FOUR MCS. AND SOIL CONDUCTIVITY OF 5×10^{-14} emu

References 5 and 17

1) $\lambda m = 246/5280 = .0466$ mi.

2) From p.675 of (2) and App 1 - Graph 21 of 17:

$$Esu = \frac{2\,Eo}{d}\ A$$

$$2Eo = 186.4\ (P_{kw})^{\frac{1}{2}} = 5.88\ (P_W)^{\frac{1}{2}}\ mv/m\ @\ 1\ mi.$$

3) So unattenuated $Esu = 5880\ uv/m/\ (watt)^{\frac{1}{2}}$

4) To calculate A (for e = 15 and σ of 5×10^{-14} emu:

$$x = \frac{1.8 \times 10^{15} \times 5 \times 10^{-14}}{4} = 22.5$$

$$b = \tan^{-1} \frac{e+1}{x} = \tan^{-1} 16/22\tfrac{1}{2} = 35.3^{\circ}$$

$$p = \frac{\pi d}{x\lambda} \cos b = \frac{\pi}{22.5} \times \frac{\cos 35.3}{.0466} = 2.45$$

From curves : A is .25 to .22

Therefore $E = 1400\ uv/m/\ (watt)^{\frac{1}{2}}$ at one mile

5) And d to 100 uv/m:

$f(p)/p = .1 \times 100/1400 = .00715$

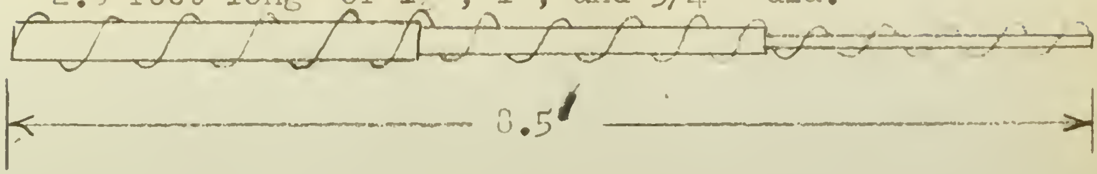
from which p = 9 or 9/2.45 = 3.68 mi.

6) And the distance to an S 9 signal into a $\lambda/4$ vertical grounded antenna is the distance to:

4.4 uv/m = 16.3 mi.

FIGURE XX

68.7 feet # 16 enam. wound on phenolic forms
2.3 feet long of 1½ , 1 , and 3/4 " dia.



Forms used so that the Q of each section could be measured separately, and the R_1 eff determined

9.3 Mc. Helical (Built to determine validity of Resonant frequency design equation (24)

Same forms as above with 160' # 15 wound

Helical I

140' # 10 insulated house wire wound on 1½", and 1 ¼" forms with four lucite strips laid lengthwise along forms. Top section replaced by aluminum 3/8" tubing

Helical II

DETAILS OF EXPERIMENTAL CONSTRUCTION

FIGURE XXI